Engineering Case Library

ECL 69A

Computerized Traffic Control

City of San Jose - IBM Corporation

Abstract

Early in 1964, the city of San Jose, California entered into a joint agreement with the IBM Corporation to conduct a study to determine "if it is functionally and economically feasible to apply a digital computer to the control, surveillance and evaluation of a traffic control system". (Part A) A total of 59 signalized intersections were controlled by a centrally located 1710 computer system (Part B) under a variety of control strategies. (Part C) Results of the study were such that, in July 1966, the city decided to install a modified IBM system for the regular control of certain intersections. (Part D)

Prepared at Stanford University during the 1966 National Science Foundation Summer Institute conducted by the Design Division, Mechanical Engineering Department. This case was prepared by Donald O. Covault, Georgia Institute of Technology, Gerald A. Fleischer, University of Southern California, and Paul F. Williams, San Jose State College, participants in the Institute. The assistance of Mr. Paul Haddon and Dr. Albert Chang of the IBM Corporation, and Mr. James Boring, Traffic Engineer of San Jose and Mr. Karl H. Vesper of Stanford University was indispensable. The permission of the IBM Corporation and the city of San Jose to use this case for educational purposes is greatly appreciated.

Automatic Traffic Control

San Jose

San Jose, California, a progressive commercial and retail center, is located about 50 miles south of San Francisco in Santa Clara County. Its population increased from 95,000 to 258,000 during the period 1950-62, had grown to 360,000 by mid 1966, and it is expected that the population will exceed 1,000,000 by 1980.[1] In 1962, the county population was 760,000 with approximately 420,000 registered vehicles.

The city is governed by a Council of seven people, one of whom serves as Mayor, and a City Manager responsible to the Council. A number of functional departments report to the City Manager, among which is the Public Works Department directed by Mr. A. R. Turturici. A departmental reorganization in January, 1965, created a Traffic Engineering Division. Jim Boring, Traffic Engineer and Head of this Division, reports to Mr. Turturici.

The Traffic Engineer

Jim Boring was born and raised in San Jose, California. After serving in the Navy during 1948-53, he enrolled at San Jose State College and, in 1957, received his B. S. in Civil Engineering.[2] Jim then was employed by the city of San Jose, reporting to Mr. Richard Blackburn of the Street Design Division, Public Works Department. When the division was reorganized in January, 1965, Dick Blackburn was assigned new responsibilities in another division; Jim was given the title of "Traffic Engineer" and selected to head the newly formed Traffic Engineering Division.

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[1] A minor portion of this increase is due to extension of city limits.

[2] Jim's post-graduate education consists of certain night courses relating to Civil Engineering and, further, a period of study (1961-62) at the Yale University Bureau of Highway Traffic.

Some Early History

Recognizing the pressing need for improvement in traffic conditions in the city—especially in the central business district (CBD)—the City Council authorized a traffic study to be conducted by the firm of Wilbur Smith and Associates, consulting engineers specializing in transportation problems.

A map of the major routes at the time of the study (early 1963) is presented as Exhibit A-1; the traffic flow in the areas of specific interest is shown in Exhibit A-2.

The final report of the Smith study, dated September 16, 1963, included the following principal recommendation (among others):

> "Modernize existing traffic signal system, utilizing multi-dial, triple-offset interconnected fixed time signal control equipment throughout."[3]

Exhibit A-3, quoted directly from the Smith study, provides additional information relating to this recommendation.

Dick Blackburn, Jim Boring and certain other of their co-workers had long considered the possibility of using electronic computers to control traffic signals. By late 1963, however, these engineers were aware of only a single precedent: a joint venture between the city of Toronto, Ontario, and the Traffic Research Corporation, a Canadian-based consulting firm. Little information about the Toronto project could be obtained at that time, but Jim believed that the project presumably included a digital computer for traffic control. Jim also knew that the equipment being used was not that of the IBM Corporation.

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[3] A description of signal control equipment is provided in Part B.

IBM maintains a major research and production facility within the city limits of San Jose. (They are located outside the central business district on the southern border of the city.) Account representatives are frequently assigned to visit local organizations, both private and governmental, in order to service existing accounts and to generate new business from prospective customers.

As the result of IBM's long experience in the application of digital computers to process control, several of the company's representatives recognized the possibility of adapting IBM equipment to the operational control of vehicle traffic. If this new application proved to be economically and technically feasible, of course, a potentially large and profitable marketing opportunity would result. However, by the end of 1963, no municipal government had agreed to purchase IBM equipment for this purpose nor were there any active research projects directed to computerized traffic control.

In November 1963, Stan Dickinson, one of IBM's local account representatives in the San Jose area, visited Jim Boring and Dick Blackburn in Dick's office at City Hall. During the course of the conversation, Stan mentioned the possibility of forming a joint study team to investigate the possibility of using IBM computers (and associated equipment) to control traffic signals in the city.

"Well, we've been thinking along those lines for some time ourselves," said Dick. "It sounds to me like it might prove very fruitful."

"I like the idea, too," Jim agreed. "Toronto is doing something along these lines. If we can get the support of the City Manager before the Council, I think that they'll go along with us. Once given the chance, I think this idea will prove itself."

After some additional discussion, they agreed to continue informal discussions and, in the meantime, Stan would prepare a written proposal for consideration by the City Administration.

Several weeks later, Stan forwarded a proposal in memorandum form (Exhibit A-4) to A. P. Hamann, the City Manager. Dick and Mr. Turturici had discussed the project earlier with Mr. Hamann, and so the memorandum was expected.

Agreement

Based upon Dickinson's proposal of December 13, Hamann asked permission of the City Council to enter into agreement with IBM to carry out a joint research study. The traffic engineers (Jim Boring and Dick Blackburn) indicated that, since the city "would be putting in the interconnects anyway," and since they would be "upgrading the system as recommended in the capital improvement program", the proposed research effort would "only result in an additional cost to the city of about $50,000 for a one-year program". Most of this expense, they claimed, would be due to the hiring of three electricians who would be used to install detectors and controllers and make other appropriate modifications. It was also noted that, although the services of a traffic engineer and two computer programmers would be needed, these people were already on the city payroll and hence no addtional expense would be incurred.

The City Council, at its January 1964 meeting, authorized the City Manager to proceed with the preparation of an appropriate contract. This was done and, in June 1964, an agreement was signed by the city and IBM. (During this six month interim period, while the attorneys carried out their negotiations, Jim, Dick and the IBM personnel continued with their technical discussions.)

The original contract specified completion of the project by June 1965, with provision for a six month extension if suitable to both parties. (Such

an extension indeed proved necessary, and the contract was later further extended through June 1966. At the time of preparation of this case—September 1966—the contract had been extended once again through December 1966.)

According to the terms of the contract, the responsibilities of the two parties were as follows:

1. Equipment
   a. San Jose supplied:
      Detectors; controllers and their modifications; communication lines; communication line protection equipment; installation and maintenance of all items.

   b. IBM supplied:
      The 1710 Control System; special interface equipment for detectors and controllers; installation and maintenance of same.

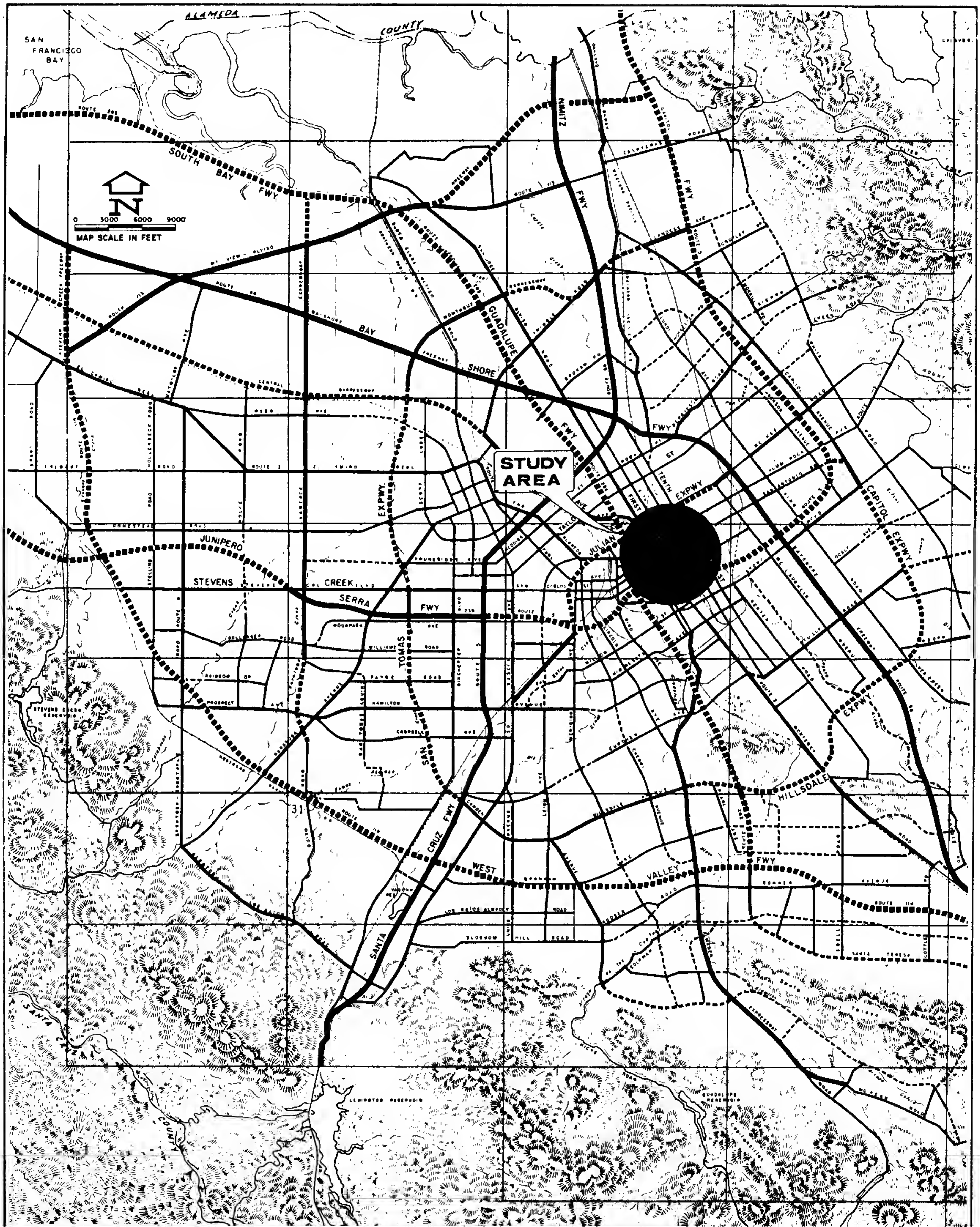
   c. Jointly supplied:
      The special display panel.

2. Manpower
   a. San Jose provided:
      Two programmers; a traffic engineer; drivers for the floating car; installers, maintainers and analysts.

   b. IBM provided:
      A site manager; programmers (from 4 originally to 1 at present); a statistician at Kingston, New York; a research engineer at San Jose; designers and consultants.

3. Space
   San Jose provided:
   The computer site, at the corner of Park and River Streets, including furniture and air-conditioning.

4. Other facilities
   IBM provided computer services for analysis work at San Jose (1401) and at Kingston, New York (7044, 7094 and 1401). This included tapes, disks, and operators. Reproduction facilities and secretarial assistance were also provided by IBM. The burglar alarm was jointly provided by both the city and IBM.



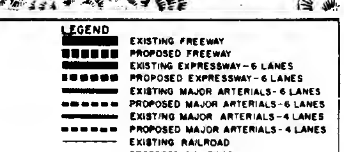


Exhibit A-1

MAJOR ROUTE MAP

Source:

San Jose Traffic Study

Wilbur Smith and Associates

September 1963

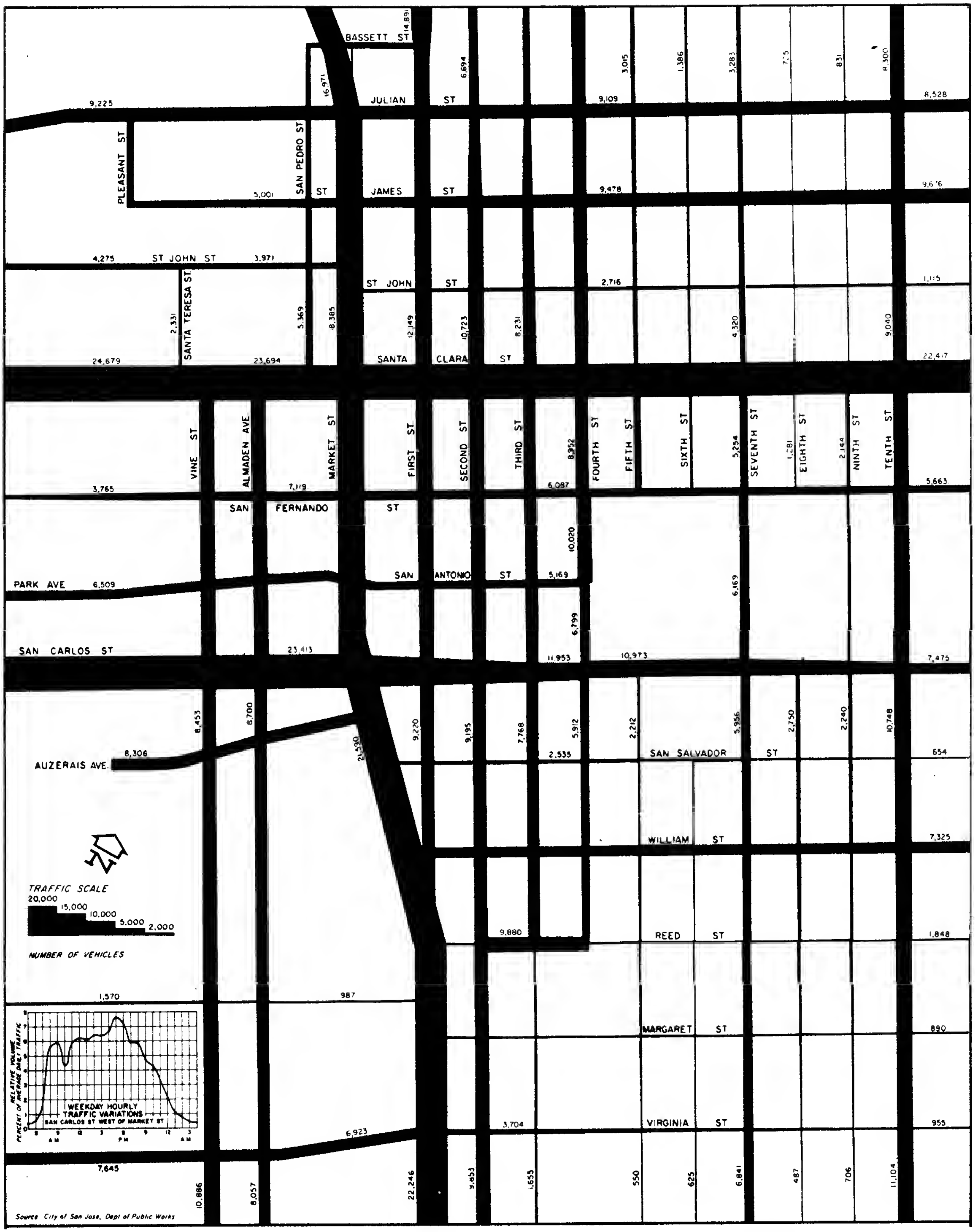


Exhibit A-2

TRAFFIC FLOW - 1962

Source:

San Jose Traffic Study

Wilbur Smith and Associates

September 1963

EXHIBIT A-3

Discussion of Recommendation

Wilbur Smith and Associates, San Jose Traffic Study

September 1963

Traffic Signal System

The existing traffic signal control equipment is inflexible and therefore unable to handle the changing traffic patterns over the course of a day with maximum efficiency. Because the peak hour intersection traffic volumes are a controlling factor in signal timing, present signal settings can be expected to create some inconvenience during low volume periods. This condition in part explains the use of flashing signals in the early evening hours at certain locations. In addition, the lack of interconnecting cable to all signal locations makes it impossible to coordinate all locations for progressive traffic movement.

Approximately 50 of the study area traffic controllers are of a recent design permitting continued use and expansion of function. All other controllers should be replaced. By the addition of the necessary supervisory circuits and suitable jack-mounted timing units and relays, the 50 units can become three-cycle triple off-set controllers permitting variations in cycle lengths and percentage of the "green time" assigned to the approaches, and changes in timing governing the progressive movement of traffic. These basic changes would offer a much greater range of operating possibilities than is now possible. With 60 second cycles this program affords off-peak traffic 25 miles per hour progressions on selected arteries. However, the very flexibility of the recommended equipment suggests that subsequent day to day adjustments by the City's traffic engineers will finally develop the precise timing schedule for the most efficient traffic operation, throughout the day.

It will also be possible to use these newer controllers, with minor modifications, as part of a future "traffic responsive" network affording full flexibility of operation. When the demands of traffic require the installation of such a system, cycle lengths, green time percentages, and progressions will be determined on the basis of information transmitted from sampling detectors to computers. Signal programs conforming to unexpected fluctuations in traffic will be possible. Differential off-sets at the signal controllers could be provided for traffic flow during inbound and outbound peak periods, or changes in green times for varying side street volumes could be programmed, for example.

Functional supervision of the various intersection controllers can be accomplished by direct interconnection of cables, by means of telephone leased lines, by use of high frequency radio signals, or with a combination of these methods. The essential factor required is the provision of interconnection for coordination.

EXHIBIT A-4

Facsimile of

IBM Proposal to City of San Jose

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IBM
Data Processing Division
1955 The Alameda
San Jose 26, California

Telephone: 258-2620

December 13, 1963

Mr. A. P. Hamann
City Manager
City of San Jose
San Jose, California

Dear Mr. Hamann:

Earlier, this year IBM requested permission to work with the San Jose City Traffic Department to determine the feasibility of installing an advanced computer system to solve existing and future traffic requirements. The results of this joint effort have resulted in the following conclusions:

1. The cost of street modifications to increase traffic flow is becoming so costly as to negate its value in many instances.

2. Better utilization of existing facilities would be possible if they could respond on a more timely basis to changes in traffic patterns. We feel that this potential improvement may increase street capacity by a significant amount thereby <u>delaying</u> costly major modifications.

3. In order to properly solve traffic problems, the Traffic Department needs a better way to accumulate volume counts and to simulate different solutions to determine the most effective methods of control without having to physically install each system.

We are convinced that the use of a digital computer tied directly to street detectors, sampling traffic flow every few seconds and setting the signals within a whole network offers substantial improvements in both performance and cost over any other available technique.

But frankly, this concept has not been field tested anywhere in the United States. We feel that there could be strong mutual benefits to both IBM and San Jose City in exploring this advanced technique together. There has been keen interest displayed by the Traffic Department and it is for this reason, coupled with the nearness of our research facilities that makes us feel we would like to develop this application in San Jose.

Basically the areas of responsibility would be as follows:

1. IBM will provide a full-time staff of five men. This team has already been selected and has been working the past couple of months to develop a detailed proposal.

2. IBM will provide a 1710 Control System computer that would usually lease for approximately eight thousand dollars per month without charge. The installed duration will be for the calendar year 1964 but might be extended at the end of that time if mutually agreeable to both parties.

3. The City of San Jose will provide the necessary street detectors, signal box modifications and communication lines. This cost has been estimated by your staff at fifty thousand dollars with at least 25% directly recoverable at the end of the study.

4. The City would also provide the services of <u>one traffic engineer</u> and one to two programmers to work with our staff on a full-time basis.

The scope of the study would be divided into two separate areas. The first would include San Carlos Street from the downtown area to near Route #17. The parallel streets of Park Avenue and Auzerais would be included. We would hope to have this under computer control by the second quarter of 1964. Phase two would deal with the downtown network.

Mr. A. P. Hamann
Page 3
December 13, 1963

It is our intent that the study provides the following:

1. Traffic data to your City that is not presently available

2. Allow both of us to determine the degree of improvement possible using a digital computer control technique

3. For the Traffic Department to evaluate several different solutions to traffic problems using the computer at minimal cost

The results of this study will be the mutual property of the City and IBM and we trust this project will develop into a model demonstration point of advanced thinking and concepts being utilized to solve a problem confronting virtually every city in the United States. At the conclusion of this study, IBM will remove its equipment and the City is under no obligation to lease such a system.

If for any reason the computer fails, the signals are engineered to return to their normal mode of operation. IBM divests itself of any responsibility for an accident within the control area regardless of cause.

Also, while the 1710 system is installed, it must be restricted to the traffic study problem and will not be available for general engineering applications.

We are preparing a detailed outline of our plans to submit to you shortly. But, I wanted to take the opportunity to update you on our thinking at this point.

I am looking forward to sitting down with you to answer any questions that may have come to mind and to working with you and your staff in the months ahead.

Sincerely,

(signature)

R. S. Dickinson
Account Representative

RSD:ab

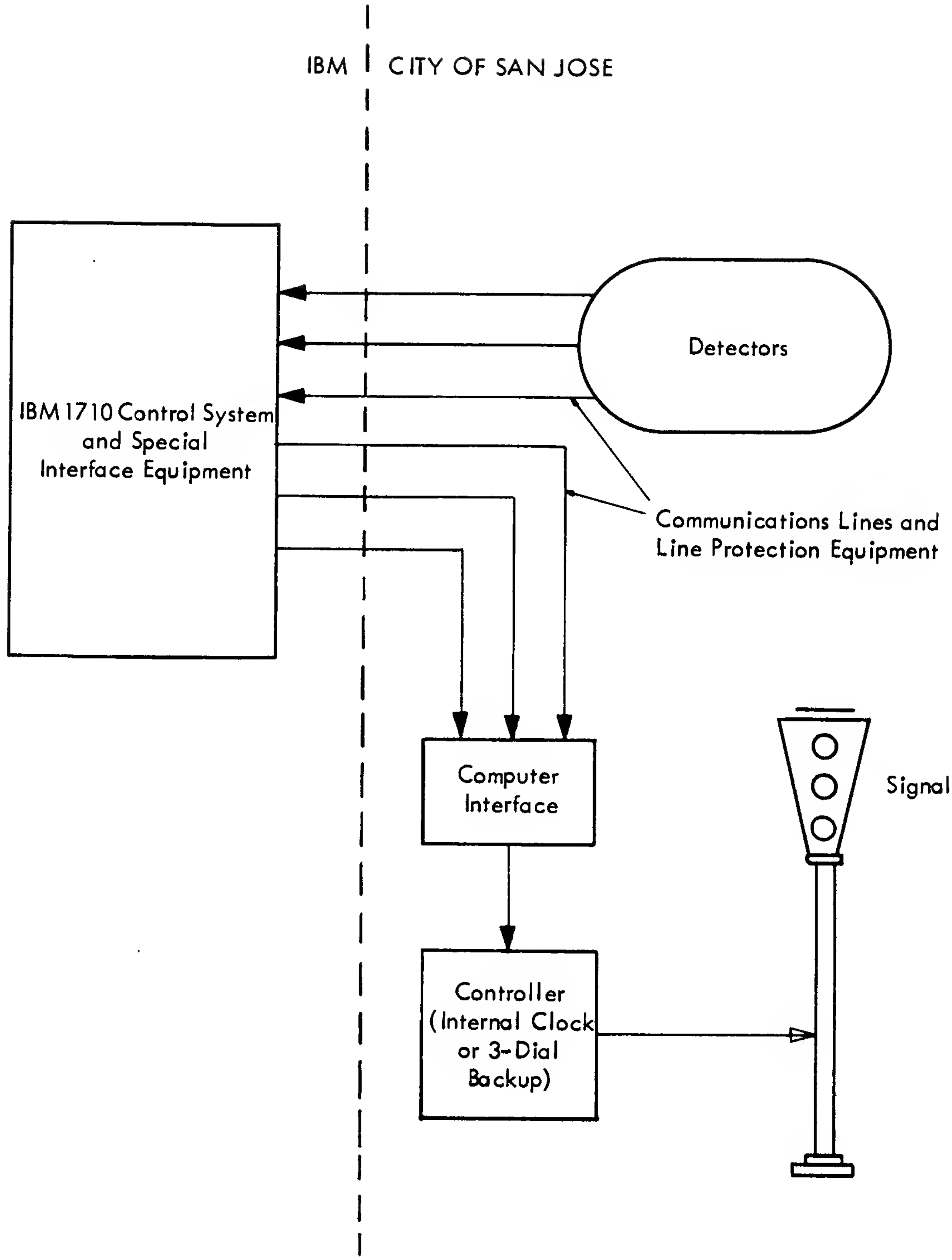

Exhibit A-5. DIAGRAM OF EQUIPMENT RESPONSIBILITY

Source: IBM Corp., "San Jose Traffic Control Project Progress Report," May 1966

Computerized Traffic Control [1]

City of San Jose - IBM Corporation

In February 1964, after the initial (but not formal) decision to proceed with the traffic control project had been made, Jim Boring started to seriously consider the methods and techniques under which the feasibility of the computer system proposed by IBM might be evaluated. There were approximately 250 signalized intersections in the city, some of which were isolated from each other by several blocks whereas others were adjacent. Most of the signalized intersections are located in the downtown business district. Most of the problems which are associated with traffic movement and parking are also located in this area. Certain arterial streets have also exhibited serious problems related to traffic movement.

[1] Much of the material in this section dealing with equipment is taken from the report, "San Jose Traffic Control Project Progress", by the IBM Corporation, May, 1966.

Prepared at Stanford University during the 1966 National Science Foundation Summer Institute conducted by the Design Division, Mechanical Engineering Department. This case was prepared by Donald O. Covault, Georgia Institute of Technology, Gerald A. Fleischer, University of Southern California, and Paul F. Williams, San Jose State College, participants in the Institute. The assistance of Mr. Paul Haddon and Dr. Albert Chang of the IBM Corporation, and Mr. James Boring, Traffic Engineer of San Jose and Mr. Karl H. Vesper of Stanford University was indispensable. The permission of the IBM Corporation and the city of San Jose to use this case for educational purposes is greatly appreciated.

The decision to signalize an intersection is determined by Boring and his professional staff after first comparing the traffic characteristics of the intersection to be signalized with well known national warrants. If the intersection should be signalized when compared to the warrants, then the final decision to signalize is made by the staff after such items as cost, budgets, and other problems are considered.

Most of the traffic controllers which were in existence consisted of relatively old one and three-dial fixed-time controllers.[2] There was relatively little traffic-actuated equipment being used by San Jose.

In March 1965, the Traffic Engineering Division was formed with Boring as its head. The Traffic Engineering Division presently has 30 persons working for it. Six of these persons are professional traffic engineers and the remaining personnel consists of technicians and clerical workers. Mr. Eugene Mahoney, who is in charge of the Operations Research Section of the Department, was assigned by Mr. Boring to work on the Traffic Control Project with Mr. Paul Haddon of the IBM Corporation.

After discussions with Boring and his staff and analysis by Eugene Mahoney, meetings were held with Mr. Paul Haddon (Data Processing Division, Federal and State Government) of IBM and a plan for design of the system to be evaluated was made. In addition, Mr. Haddon evaluated the computer hardware requirements to control the selected system. This group determined that the study was to be divided into two phases. Phase I study was to be primarily

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[2] One-dial fixed-time controller: A controller which operates on only one allocation of time for red, amber, and green. This controller operates with one cycle time.
Three-dial fixed-time controller: A controller which operates at different periods on one of three dials. Each dial may have a different cycle and a different allocation of time for red, amber, and green.

concerned with an evaluation of arterial street operation (open network) with computer control, and the Phase II study was to be concerned with an evaluation of a network of streets (closed and open network) with computer control.

As shown in the diagram in Exhibit B-1, Phase I covered the first part of the study, which included 32 intersections, most of which were on San Carlos, the remainder on Auzerais and Park. Phase II included the complete project area, incorporating Phase I, and adding 27 more intersections, which were in the downtown area. Phase I used some 200 detectors, while Phase II required 400 detectors.

System and Equipment Description

General System Description

There were many factors to be considered in the design of a traffic control system. The central control equipment, the communications link and the equipment on the street each have to be studied from a localized viewpoint, as well as considering their effects on the entire system. Direct costs, reliability, simplicity, maintainability and lead times must be weighed along with the desired functional requirements of the system. After making several passes using different communications schemes and devices, a decision was made by Haddon and Boring which seemed to represent the optimum balance for this particular situation. This decision resulted in a process control computer at the central site, a multi-wire communications link to each controller and simple modifications to existing controllers. Direct wire was also brought to the computer from each detecter. These elements are all described in detail in this section.

Equipment Description

Central Computer (Refer to Exhibit B-2)

The IBM 1620 is the computer portion of the IBM 1710 Traffic Control System. This computer contains 60,000 digits of core storage which houses the control programs and data storage necessary to control the entire traffic network.

All arithmetic functions, logical decisions and commands for traffic signal control are handled in this unit. Every device in the entire traffic complex operates under the complete and continuous monitoring and/or control of the IBM 1620 Central Processing Unit.

Directly attached to (and part of) the IBM 1620 is an alphameric console typewriter. Its primary function in this system is as an indication and record keeping device.

IBM 1311 Disk Storage Drive

The IBM 1311 is used to store the large volumes of data generated by the system. It also contains programs, subroutines and complete traffic operating tables required by the system. The disk pack is interchangeable with others and can store 2,000,000 digits of information. Access to the disk is on a random basis; a 500 instruction program can be brought into 1620 core storage in as little time as 300 milliseconds.

IBM 1711 Data Converter

The IBM 1711 is an intermediate processing station. It controls the interrupts to the 1620 computer, and houses the pulse counters that are used to accumulate detector information. It also contains the Real-Time Clock for the system, which regulates the basic timing for the entire system.

IBM 1712 Multiplexor and Terminal Unit

A variety of binary devices may be actuated or entered into the IBM

1710 Control System via the IBM 1712 Multiplexor. Manual switches and buttons may be used to control specific operations. The 1712 in this system is used as the terminating device for all system entry and exit points. It also contains the Contact Operating Points and Pulse Counters for the controllers and detectors. High speed Contact Sense Points are used for the main street green monitor.

IBM 1443 On-Line Printer

The IBM 1443 Line Printer is capable of printing 120 character lines at a rate of 150 lines per minute. In addition to listing the IBM 1710 control programs during the assembly process, the printer is used for the rapid printing of diagnostic and statistical information during actual control operation, and for the results of off-line summaries and analyses.

IBM 1622 Card Read/Punch

Capable of reading at the rate of 250 cards per minute and punching 125 cards per minute, the IBM 1622 provides a convenient means of entering data and programs into the system.

The punch unit of the IBM 1622 can be used to punch statistical and logging information regarding the operation of the traffic system. These cards can be entered back into the system (via the reader) for comprehensive statistical analysis.

IBM 1713 Manual Entry Unit

The IBM 1713 provides a convenient method of entering up to 12 digits of information into the IBM 1710 System. These 12 digits can be interpreted by the system as instructions, data or requests for particular system responses. Operator entry may be initiated by the IBM 1710 Control System or by the operator (or engineer) located at the Manual Entry Unit. The IBM 1713 may be located remotely from the IBM 1710 System. The 1713 has been used to

interrogate detector and count information, and to make changes to the system during the on-line progression technique.

IBM 1715 Digital Display Unit

The IBM 1715 provides a continuous 4-digit display to the operator or engineer. As with the IBM 1713, the IBM 1715 may be located remotely from the IBM 1710 System. The display has been used to show the requested values of speed, volume, stops, splits, cycle lengths and offsets after interrogation by the 1713.

Display Board

The display board was assembled by joint efforts of city and IBM personnel. It shows a map of the control streets, and at each intersection there is a light which is wired directly from the relay that comes from the controller monitor line. The light is either green or red and indicates the east-west "green" condition or east-west "red", depending upon the particular intersection under control. The board has proven most valuable in checking progressions from the computer central, and because it is wired directly, can be used at all times, when the computer is not controlling the system. There is also a row of neons that show which intersections are under control.

Special Interface Equipment

Because of the distances involved, the signals from the controller monitor lines and from the detectors could not be entered directly into the 1712. IBM built a special relay interface that operates with a power supply to serve as a matching device for these signals, IBM wire contact relays are used.

Controllers

Pretimed, expansible controllers are installed at all intersections in the study areas. Prior to the study eight electronic volume-density controllers were in use on the western leg of San Carlos Street. These controllers were

replaced with pretimed, expansible controllers and the electronic controllers either installed at non-computer controlled intersections or used as spares.

The decision to replace these controllers was based primarily on the desire to have a three dial interconnected system for use during periods when the computer was not controlling the system. The city also was able to make good use of these units as spares for other locations. A final reason was that pretimed controllers are simpler to control than electronic types when using a computer, even though an interface for the latter was designed and tested.

All the controllers are Econolite type "F" expansible controllers or type "F" with flashing don't walks. Three dials are installed in each controller in an interconnected system. The pretimed master is located at the computer site. During non-computer controlled periods the intersection controllers are controlled by the three dial master system, the dial currently in use being selected by time-of-day.

All the controllers were modified to adapt them to computer control. This was done by installing three relays in each controller. One relay, the hold on-line relay, is used to disconnect the dial drum advance and drum release contacts from the drum motor when the dial reaches the main street green key, where it rests during the computer control operation. The hold-on-line relay also connects the drum motor to the advance relay contacts. The advance relay, when operated, steps the controller drum one interval. The hold-on-line relay and the advance relay are operated, over the cable interconnect, by the contact operate relays in the computer.

A monitor relay was added in parallel with the main street green (MSG) lamp, and during the MSG interval, this relay's contacts are closed. This contact closure is transmitted over the cable interconnect and sensed by the contact

sense points in the computer. By adding these three relays the computer can disconnect the local controllers' timing circuit, step the controller through each interval and vary the time of each interval. It also checks the controller during the MSG intervals to verify that the controller has responded to each advance pulse sent during the previous cycle by the computer.

If the computer senses a controller not responding to its command, that controller is released by the computer. The local controller then operates on the preselected dial, or if the controller is inoperative, maintenance personnel are called to repair the controller. In either case, the computer prints a message that the computer has relinquished control over this controller and the time this action was taken.

In addition to the three basic relays, several three phase controllers on San Carlos Street were provided with one additional computer controlled relay. This relay, the "all-signals-red" (ASR) relay, is used to turn all signal indications red while this relay is operated. This relay would be used to allow the computer to skip a phase when there was no demand on that phase. Expansion capability was provided in some controllers so that another relay could be added. This relay could provide two selectable special turning movements.

By using these controller modifications, the computer can control all of the signal intervals and coordinate any intersection with another intersection or any group of intersections. Also, in the event of a computer failure or communications failure, the controllers will "fall back" to the three dial, pretimed, interconnected control system. The three dial interconnected system is used during non-computer controlled periods of the day.

Detectors

Two types of detectors are used in the Phase I portion of the project:

loop detectors and pressure pad detectors. For Phase II, only loop detectors were added.

All detectors previously installed in the study area were incorporated into the project. This included all pressure pad detectors and some loop detectors in the Phase I area. In the area added to comprise Phase II, there were no detectors originally.

The pressure pad detectors are all permanent, embedded, non-directional types that cover one lane. These detectors are primarily used to measure volumes in conjunction with the computer. In a few cases, they are being used to measure stops and delay.

The most prevalent type of loop detector is the RCA Ve-Det 4-Pak. These detectors are transistorized and provide a mercury wetted relay output. The detector oscillator is crystal controlled and crystals of various frequencies are used to avoid interference between nearby loops. The detector amplifier senses the change in the loops' effective inductance due to a vehicle passage by a phase shift detection circuit. The phase shift detection is amplified and closes the output relay. Four detector amplifiers may be powered by one detector power supply and the amplifiers and power supply are packaged in one case. The loop detectors are used to measure stops, volume, delay, speed (one loop or paired loops), and lane occupancy, by sending their inputs to the computer which makes the calculations.

Both the pressure pad detector and loop detector provide a contact closure output. The contact closure is transmitted to the central computer as a grounded signal wire. The grounded wire picks a relay at the central site, repeating the detector's relay closure. The relay contacts at the central site are connected to the 1710's pulse count input, and the 1710 computer interprets and measures these contact closures and duration of closure as speed, volume, etc.

The Communications System

Every controller in the Phase I and Phase II area of the project was connected to the computer over communications cables. All the detectors were also connected to the computer by these cables. The signals transmitted over cables are all d.c. 96 volt pulses. Each cable is a multiconductor shielded cable, containing 6 pair to 100 pair of twisted number 22 gauge wire conductors. A large conductor and the cable support are used as the communication common and each conductor is used with the common as an unbalanced transmission line.

A voice communication system is incorporated in the cable so that project personnel can talk to the site from each controlled intersection. This is done by plugging a sound powered phone into a jack within the intersection controller cabinet. Four of the cable wires are used in this application, and are common to all locations. Each controller has a minimum of three wires connected to it, in addition to the system common. Each detector has one wire per amplifier returning to the computer, and shares the same common d.c. line with the controllers.

Each wire carries only one signal. The three signals used by all controllers are: 1) the hold or stay-on-line signal, 2) the advance signal, and 3) the main street green (MSG) monitor. The hold-on-line and advance signals are transmitted from the computer to the intersection and the monitor signal is transmitted from the controller to the computer. In addition, some controllers have a hold-on-red signal transmitted to them so that phase skip may be accomplished. Some controllers have an expansion feature allowing for a special phase selection, but this feature has not been used under computer control. Sufficient spare wires were included in all cables to allow for defective wires and future expansion.

The cable stringing was contracted by the city of San Jose to a private contractor. Cable routes were selected to minimize cost by utilizing existing structures. Over 95% of the interconnecting lines were hung on existing utility poles or placed in existing conduits and ducts. Cables hung on utility poles were of the I.M. figure 8 type and were placed in the fire alarm and police communication pole positions. In the downtown area where underground ducts were available the interconnecting cable was placed underground. All cables terminate at the central office site into a standard telephone type office protector. Each signal wire in the cable is protected from lightening hits and power crosses by an open space cutout and from signal crosses or signal wire grounds by a heat coil. The open space cutouts and heat coils are contained in the office protector and the protector also provides the terminating device for the cables.

The following table indicates the different tasks performed by city personnel and by contractors:

San Jose	Contractors
Installation of wire loop prototypes. Controller modifications.	Installation of remaining wire loops.
Detector Housing Design and installation of Phase I Housing.	Installation of Phase II Detector Housings.
Installation of cable in questionable situations and additional locations.	Installation of 90% of cables.
Tested detectors —bench and field.	Installed 100% of new conduit required.
	Remodeled some equipment at twenty intersections.

Several difficulties in the installation of the detectors and conduit occurred. Some of the detectors required extensive debugging. In addition the electrical workers labor union objected to non-union personnel of the

Traffic Engineer Division installing cables for the detector connections with the computer center location. These problems delayed the completion of the signal system hardware for six months.

The original contract with IBM was extended six months because of the delays in developing the system.

Control System Concept

Control Systems is the name given to that class of systems which connect cause and effect into an automatic continuous operation. A simple example is the heating system in most private homes, where the sensing instrument, or thermostat, controls the on-off condition of the furnace, which heats the air in the home, which then "closes the loop" by its action upon the thermostat. There are many different kinds of control systems, from the simple case just described to very complex chemical and missile systems. However, the following four elements are common to all control systems:

1. Information Gathering
2. Decision Making
3. Execution and Verification
4. Evaluation and Adjustment

Like other unique systems, a traffic control system imposes its own special requirements, which modify these basic elements. These special requirements arise because traffic is not uniformly or permanently predictable. There are significant variations that occur from minute to minute, as well as daily swings and long range trends. The minute to minute changes can be observed at a particular intersection; the daily swings are a result of patterns of business life in an area, and the long range trends usually reflect the growth of an urban area.

These variations are not only influenced by time, but by location and other elements. Ball games, parades, new supermarkets, parking lots and weather can all affect traffic. These effects may also vary for different

parts of a city, and to a different degree depending upon the interaction of the elements.

Working along with all these variables is the human element, which adds another unknown, and which may not allow nice mathematical predictions to function in a real life traffic environment.

For these and other reasons, the basic control system requirements for traffic control are as follows:

1. Continuous Information Gathering—to handle all of the variations.

2. Flexible Decision Making—to respond to the variations and also to keep pace with the growing body of knowledge in timing traffic signals. Decision making should not be welded to a particular physical configuration.

3. Accurate Execution and Verification—to make sure that the system is responding to the command.

4. Continuous Evaluations—of both long range and short term variations, with the ability to make emergency or planned adjustments.

More specifically, the San Jose system was designed to provide the following:

1. Electrical actuation of currently installed controllers. Actuation is accomplished by timed pulses under positive computer control.

2. Accurate timing within one second for each controller step. Timing methods interlock and guarantee minimum amber; pedestrian walk times are not violated.

3. Synchronous phasing of all signal changes, accomplished smoothly and without disruption of normal traffic flow, when responding to changing conditions or manual instructions.

4. Automatic error recovery of a malfunctioning controller with provision for return to local control (with alarming) should recovery prove impossible.

5. Real time detection and counting of vehicles in special areas. Traffic counts are stored for further analysis. Also, calculation of density, speed and other parameters is performed as called for by the control program. Selected results can be displayed as they are occurring.

6. Detection of special functions, such as railroad and fire station activities under manual or automatic control.

7. Automatic generation of traffic statistics, logging, error analysis and display of overall system performance. Logging data is in a form suitable for further detailed analysis.

8. Allowance for safe experimentation of new methods and techniques of controlling traffic, with a minimum of new programming.

9. Facilitation of communication between operators and traffic engineers with the entire controlling system. Status of the system is clearly and simply indicated at all times.

10. Maximum system utilization. During slack periods, the system makes detailed analyses to verify correct functioning of the entire system. Further statistical analysis may also be performed during these periods.

The following is added detail describing how the expanded control system requirements are fulfilled.

Continuous Information Gathering

To accomplish the desired control of the traffic network, certain information must be supplied to the computer. This required information may be divided into three types: functional data, timing data and general data.

Functional Data

Controller function data is maintained at all times in core storage of the IBM 1710 in the function tables. Each unique controller type is stored as a table and contains information regarding intersection lights that are active at each of the controller's contact positions and the current contact position of the controller. Dummy contact positions and any possible minor movements are also shown.

Each detector is directly connected to its own individual counter in the IBM 1710. As each detector actuation occurs, the detector's counter

is incremented by one. Using certain assumptions regarding vehicle length and type, approximations of velocity and traffic density are made since the time of detector actuations can be determined quite accurately.

Detector count information is entered into computer core storage when requested by the control program, and provides a complete record of vehicle demand and activity at each intersection.

Timing Data

Timing information for each intersection (and its associated controller) is provided in the timing tables. One table is provided for each controller. Table storage also contains data relative to the controller type, cycle length, cycle split, offset and dwell times desired at each contact point of the controller. Indices of allowable variation in the timing of each phase and minor movements are also provided. Cycle deviation information and control linkage (or pointer) to the corresponding function table is given. Records of controllers that have been dropped by the computer, and of recovery attempts are maintained.

General Data

Information affecting the entire system includes the time of day, time desired to change timing tables, and the desired rate of rephasing signals. This data is stored in a unique area of core storage since it is referenced constantly by all phases of the system.

Provision has been made to allow system operators to change any portion of the data or control flow of the program (subject to certain programmed restrictions and system validity checks).

Example of a Controller Data Table

Header Table (one per controller)

Length	Field Name	Description
3	Controller ID	"Name" of Controller
5	Current Time Sequence	Address in Time Table which indicates current interval of the controller
5	Beginning Address of Function Table	Address in Function Table of function for the nth intersection.
3	Total Deviation	Total timing error at this intersection. Used for correction on succeeding cycles.
6	Required Time Leaving Main Street Green (MSG)	To stay in synchronization, the controller should leave MSG at this time (fixes offset). This value increments by exactly one cycle length.
6	Observed Time Leaving MSG	Actual Clock time when controller left MSG.
6	Time Next Sequence (TNS)	Clock time when controller will be advanced.

Flexible Decision Making

Determination of a desired course of action is accomplished by a Master Control Program (MCP). The MCP controls and directs all system subroutines and handles interrupts.

As each subroutine of the computer programs completes its specific mission, it returns control to the MCP. The MCP each second calls upon a scanning routine to determine if any signals are due for actuation based upon the elapsed time since the last actuation. Control is temporarily relinquished to the Scanner which looks at each traffic signal's representation in core storage. Upon detecting a controller that is due for actuation, the Scanner places certain identification and timing data in a common communications region of core storage and returns control to the MCP. The MCP then calls upon other subroutines to accomplish actuation. To date, the decision-

making mechanism has used both table look-up techniques and real time optimization, and combinations of both. Table look-up is a process which selects signal timings[3] from a group of tables, based upon predetermined boundary values of speed, volume and/or time-of-day. In real time optimization, the signal timings are recalculated almost instantaneously, after measuring and calculating traffic parameters from the raw detector information.

All parts of the IBM 1710 Control System constantly check against a wide variety of limitations. In the timing of "walk" signal, for example, the system has a lower bound of time in which "walk" must be on (usually 7 seconds). Within that boundary, even further restrictions may apply depending on vehicle velocities, weather conditions, information supplied by traffic engineers (in the form of allowable values and percent deviation) and other considerations.

One of the most significant constraints upon the system is that disturbances must be corrected smoothly and accurately. This is accomplished by computer analysis of the absolute time deviation from normal of each intersection for each cycle, and the application of a correction factor for the next cycle. A side benefit of this automatic, constant smoothing and correcting technique is that the gentle transition from one set of timing tables to another is accomplished by merely replacing old tables with new ones.

The IBM 1710 System is constantly aware of all equipment, system and timing limitations and will operate safely within these boundaries.

---

[3]Signal timings for a two-phase operation consist of a green start time (offset), a green time, an amber time, and a red time. The sum of the green, amber, and red time is the signal cycle time. For a three-phase operation the timings consist of left turn green time, a green start time (offset), a green time, an amber time and a red time.

Probably one of the most significant results of this system operation so far has been the demonstrated ability to change decision making techniques without physical changes and with a minimum of programming disturbance to the great bulk of the programming system. This, in a time of steady technical growth, is extremely important.

Execution and Verification

The actual controlling of the traffic network is accomplished by actuating the correct controller at a pre-set time. Timing is handled by the real time clock of the IBM 1710 System as used by the MCP and the scanning subroutine. Execution of control requires that all controllers scheduled for actuation be advancedas rapidly and accurately as possible.

The IBM 1710 System actuates controllers in parallel. That is, if several controllers require simultaneous advancement, they are all advanced by one "actuation" of the IBM 1710's latching contact relays, thereby minimizing time spent in the controlling function. In some cases, advancement to the next phase is complicated by peculiarities of the controller, which may require several commands (pulses) to advance.

Verification of control is accomplished by a return pulse from the controller during the period at which it is in "main street green". This synchronization-return signal enables the computer to verify that it is in step with the operation of the controller. When the signal is sensed by the IBM 1710, the computer verifies that the particular controller is supposed to be in a main street green condition. If not, a failure has occurred either in the controller itself or in the transmission/receiving facilities of the controller. When conflicts of this type occur, the intersection is returned to local control and the operator is notified. Later attempts may be made automatically at the operator's discretion to bring the controller into step with

the program. This is done by a normal controller restart procedure.

Detectors are also checked for overcounting or undercounting. This is done by setting reasonable limits on the expected maximum value within a given time period, and by setting a limit on the length of time a detector can reasonably be expected to have a zero count before it is considered defective.

Evaluation and Adjustment

There is a threefold method for evaluating the system. This consists of real-time computer evaluation, off-line computer evaluation and floating car evaluation. Real-time evaluation is the measurement and calculation by the computer, of parameters that are used almost immediately, for adjustment to the system. Examples of this are the on-line progression and micro-loop techniques that are described later. Real-time evaluation also consists of notification to the operator of digested information, from selected detectors. The operator can then "tune" the system and make adjustments to the system by manually entering changes.

Off-line evaluation is performed by studying the reports and analyses that are generated by the computer at off-hours, and then entering changes to the tables and decision making criteria to improve the system.

The other method of evaluation for adjustment purposes is the use of the "floating car" which travels through the streets and times the results.

The Programming System

Introduction

Since a primary objective of the San Jose Traffic Study is experimentation with new methods and techniques of traffic control, the computer system program must be as general and modular as possible. Changes in one part (or function) of the program must be as independent as possible from others to avoid undesirable side effects. Changes in the method or procedure of counting and

detecting traffic, for instance, should have no effect whatsoever on the actuator or driver portion of the control program. Similarly, enlargement of the traffic network to be controlled should only require minor changes to the control system.

Isolation of the various portions of the control function is provided by the Master Control Program (MCP). The logical building blocks of the control program are not allowed to communicate directly with each other; rather, these blocks provide information to the MCP which, in turn, will direct the logical flow of information and control.

The Master Control Program is divided into separate sections (functions) called subprograms which can be independently redefined or modified as required. Some of the basic functional subprograms include:

1. Table Changer/Optimizing Algorithm
2. Scanner
3. Detector Status Reporter
4. Advancer
5. Synchronizer
6. Recovery Analyzer
7. Data Logger
8. Display
9. Operator Intervention
10. System Analysis/Performance
11. Fallback

The scheduling of the various functions (subprograms) is controlled by the Master Control Program (MCP). Exhibit B-4 illustrates this scheduling function.

Master Control Program Operation

Using the Real Time Clock as a basis, the Master Control Program (Exhibit B-5) initiates periodic tests for a requirement to advance the controllers. These tests are performed by the Scanner, which determines if the right time has arrived for a stepping action, and the Detector Status Reporter, which examines actual traffic demands. The stepping action is then performed for the MCP by the Advancer.

The MCP receives a monitor pulse once per cycle. This pulse verifies the status of the lights on the street. The time at which this pulse occurs is then related to the time at which it should occur (determined by the cycle length and offset) and any deviation is revealed. The MCP then reconciles all influences which affect the action of a controller (i.e., operator intervention, algorithm offset changes and traffic demands via detectors). If the monitor pulse does not occur, the controller is returned to local control and the operator is notified.

Scanner

When called by the Master Control Program, the Scanner examines each intersection to see if it should be advanced (obtained from the Header Table). The difference is then compared with the length of time specified by the traffic engineer for that interval (contained in the Time Tables). If this last comparison indicates that it is time to leave this interval, the Scanner records this fact for the Master Control Program.

Advancer

The Advancer is called by the MCP to move the traffic light controllers through one or more intervals in their stepping mechanisms. Should this advancing cause any intersections to leave main street green (MSG) the Advancer performs the additional function of insuring that the lights on the street are actually moving in the manner directed by the computer. The Advancer determines the condition of the lights in the intersection by examining the status of a MSG contact, which is closed when the MSG light in ON and open at all other times.

Before advancing a controller (intersection) from MSG, the Advancer checks the MSG contact for closure. If an intersection fails this closure check, its HOLD relay is dropped (thus returning the intersection to local

control), pertinent data is recorded for the Recovery Analyzer subprogram and the operator is notified. The remaining intersections to be advanced are then advanced. For those intersections which were supposed to leave MSG, a check is made of the MSG contacts to insure they have opened (i.e., actually left MSG). If an intersection fails this second check, one attempt is made to advance it. If this reoccurs during the next MSG interval the HOLD relay is dropped, pertinent data is recorded for the Recovery Analyzer subprogram and the operator is notified.

Regardless of MSG considerations, the Advancer updates the following records in the Header Table:

1. Time Next Sequenced
2. Current Time Sequence Address

For the intersections which have just left MSG, additional entries are made in the Header Table:

1. Observed Time Leaving MSG
2. (Next) Required Time Leaving MSG.

Control is then returned to the Master Control Program.

Synchronizer

The asynchronous operation on the Traffic Control Program permits one subprogram, the Synchronizer, to perform all synchronizing functions, including initial synchronization at startup, continuous damping of any accumulated errors in the system (lagging of relay responses, etc.), placing recovered controllers in synchronization, resynchronizing to a new offset progression pattern as directed by an Offset Table Change or an optimizing algorithm, etc. Moreover, the traffic engineer has control over the amount of correction performed in one traffic light cycle, thus insuring synchronous phasing of all signals without disruption of normal traffic flow.

After computing the Timing Correction (defined as the difference

between the Required Time for leaving MSG and the Observed Time of leaving MSG), the Synchronizer takes into consideration the following before computing a final correction:

1. Operator Intervention
2. Detector Counts of Actual Traffic Conditions
3. Offset Progression Table Changes
4. The Timing Correction

The Synchronizer then determines whether synchronization can be achieved more rapidly by shortening or lengthening the cycle (i.e., speeding up or slowing down to get "in step" with the progression).

Having determined the "direction" of the Total Correction, the Synchronizer examines the Time Table to ascertain which intervals in a cycle may be adjusted, and to what degree. (The degree is specified by the traffic engineer, who thereby fixes the maximum adjustment per cycle.) Finally, Adjusted Times for all necessary intervals are computed and recorded (in the Time Table) for the use by the Advancer.

Recovery Analyzer

As previously indicated, the synchronizing function involved in returning an intersection from local control to computer control is performed by the Synchronizer. However, it is obviously desirable to analyze the performance of all faulty controllers in an attempt to determine: (1) the cause and frequency of the failure; (2) the possibilities of on-line compensation/correction; and (3) the history of system malfunctions, incorporating the type of failure, the corrective actions attempted and their respective effects. These diagnostic functions are performed by the Recovery Analyzer.

Fallback

Return to local control may be scheduled or non-scheduled. For the non-scheduled condition (system equipment failure), it is imperative to avoid

erratic sequencing of signal lights. Therefore, those signals that are malfunctioning will be dropped to local control.

Smooth transition from computer to local control is easily accomplished under normal operating conditions by Fallback subprogram.

Before releasing control, the Fallback subprogram determines the current position of signal from the Main Street Monitor Line. When the signal reaches the beginning of main street green it will be dropped back to local control.

Source: IBM Corporation, "San Jose Traffic Control Progress Report", May 1966

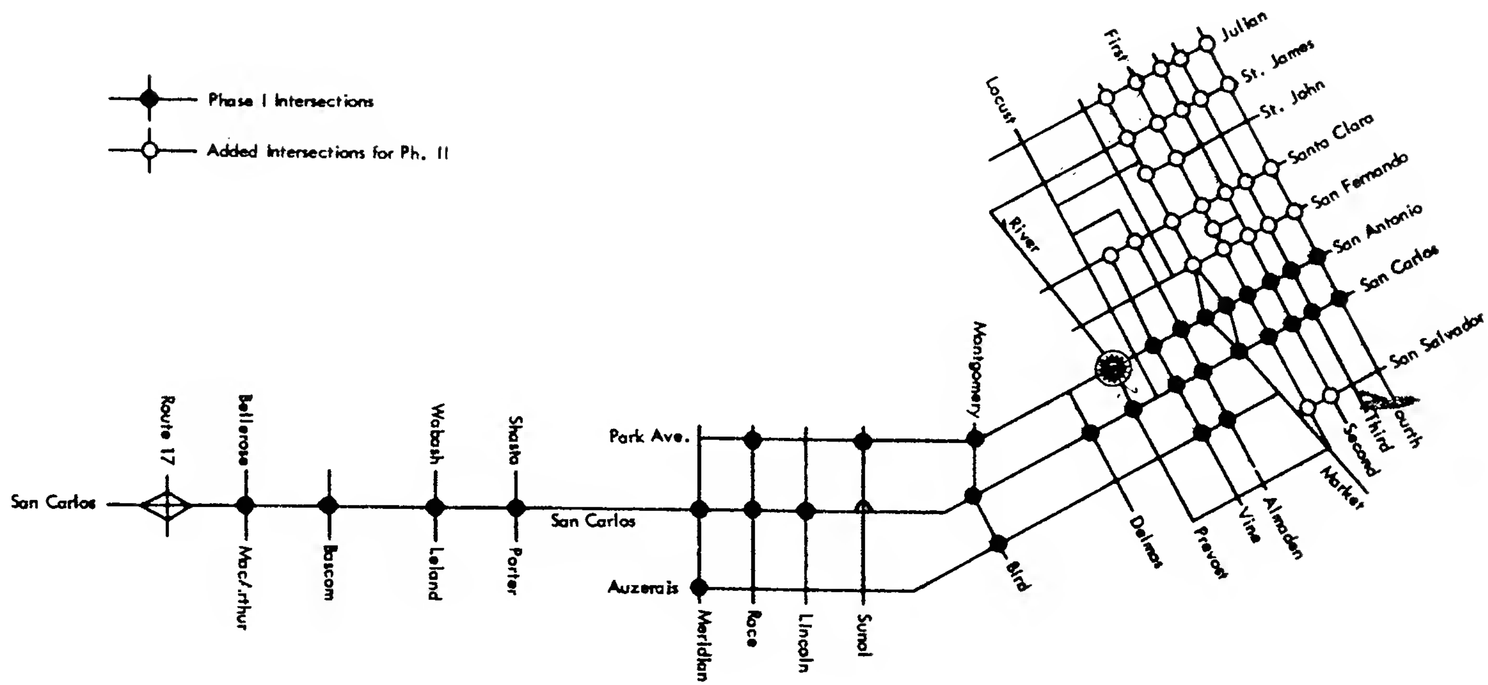

EXHIBIT B-1:ZONES FOR PHASES I AND II

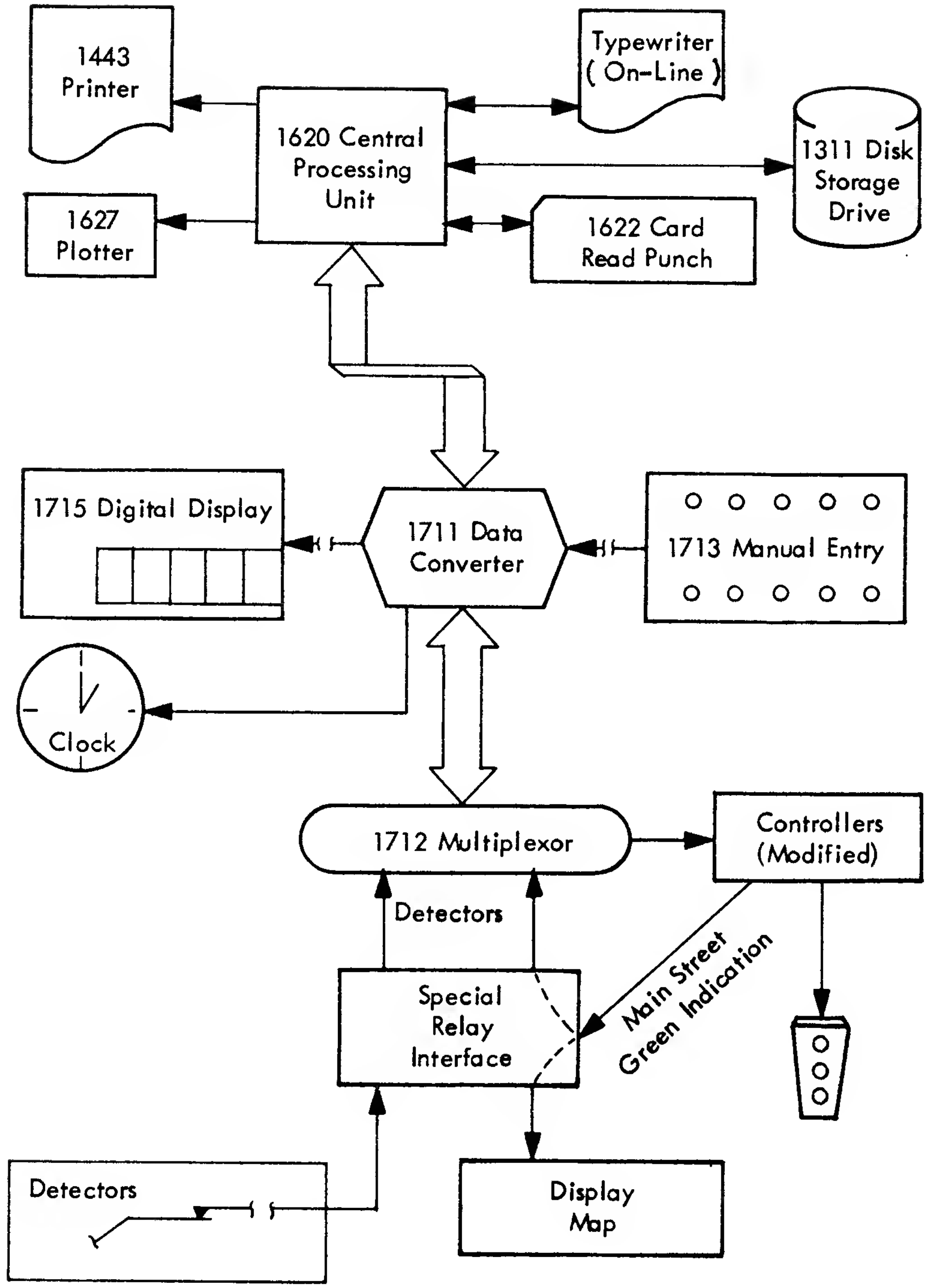

EXHIBIT B-2 SYSTEM BLOCK DIAGRAM

Source: IBM Corporation, "San Jose Traffic Control Progress Report", May 1966

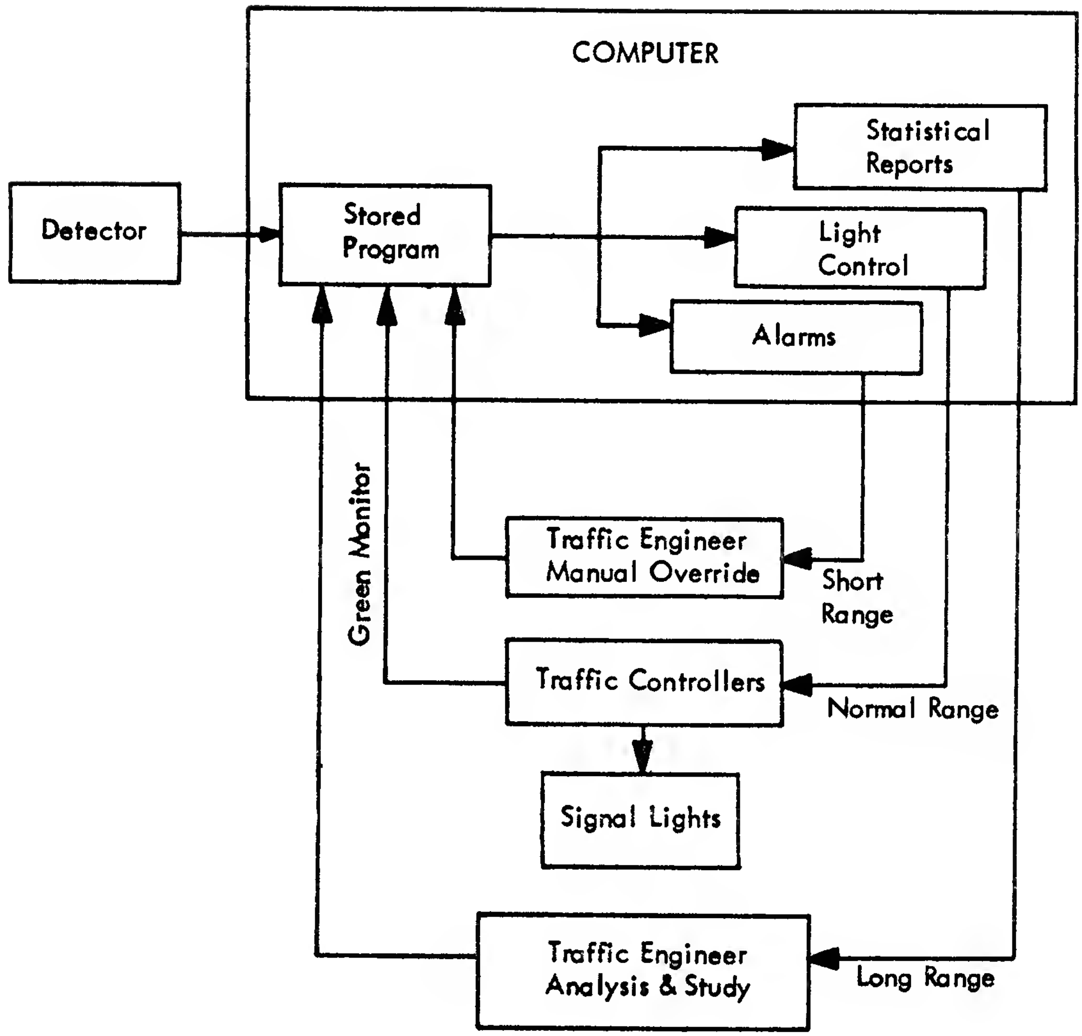

EXHIBIT B-3. CONTROL LOOP RELATIONS

Source: IBM Corporation, "San Jose Traffic Control Progress Report", May 1966

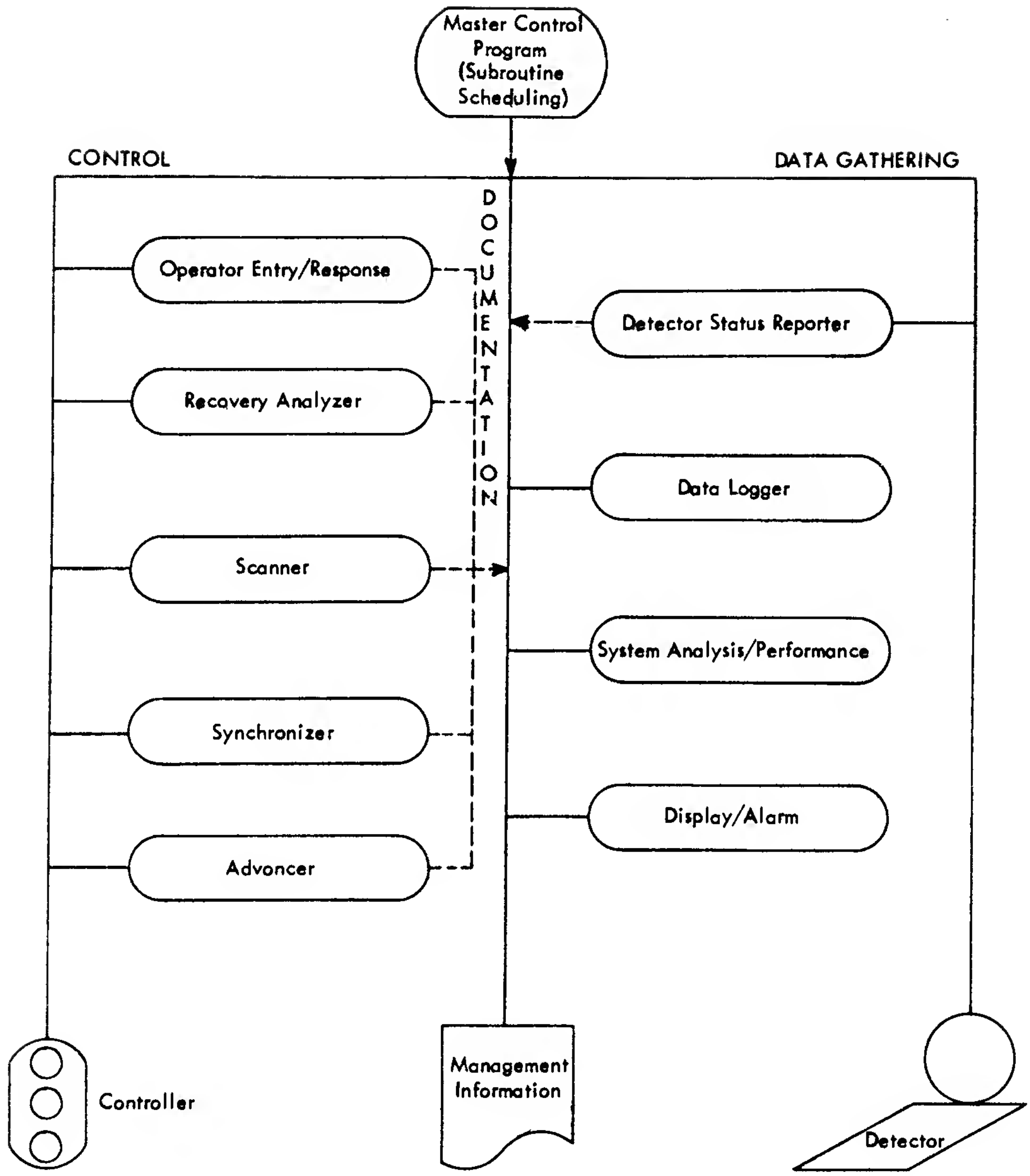

EXHIBIT B-4 MCP SCHEDULING FUNCTION

Source: IBM Corporation, "San Jose Traffic Control Project Progress Report", May 1966

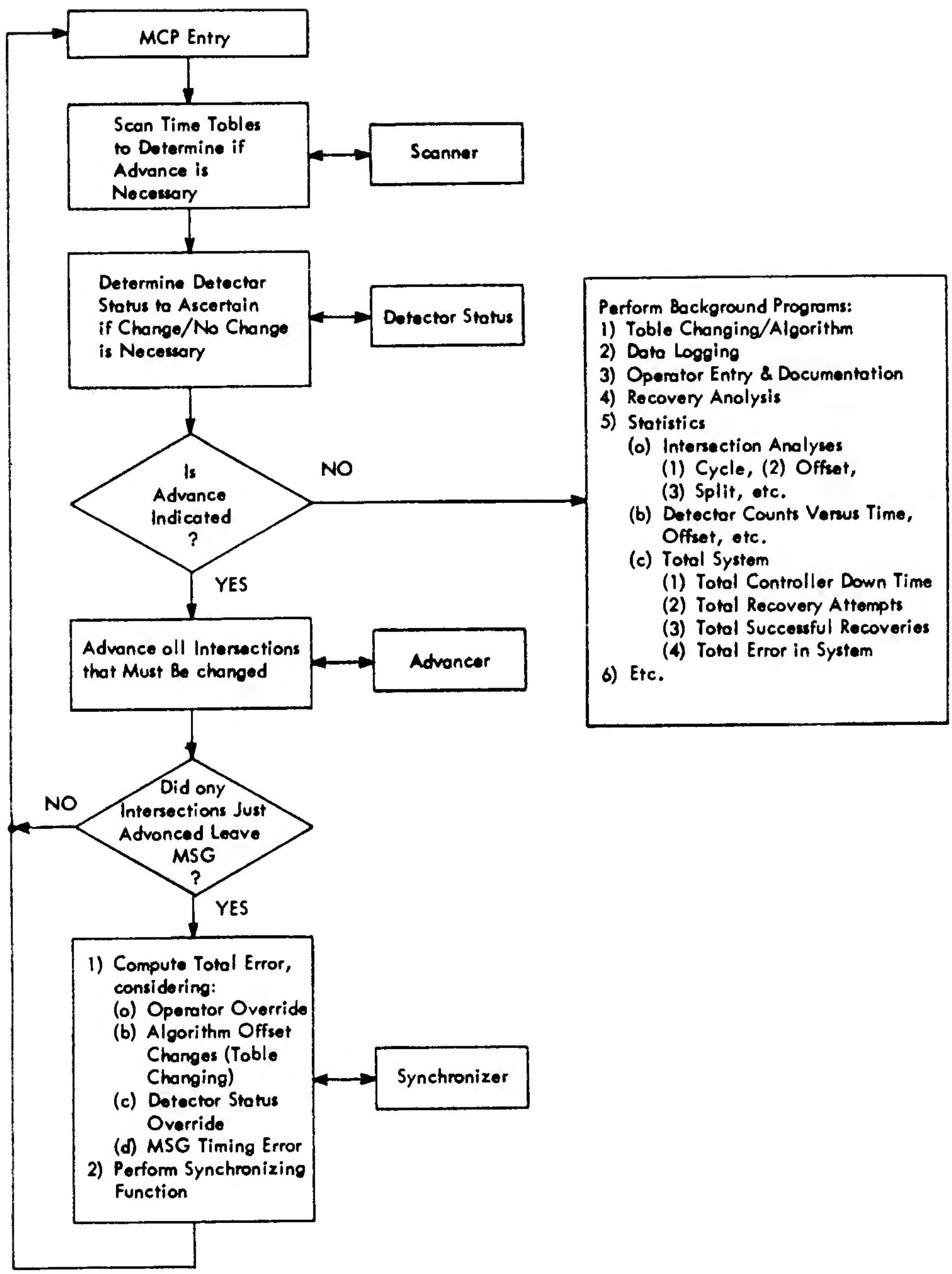

EXHIBIT B-5 MASTER CONTROL PROGRAM

Source: IBM Corporation, "San Jose Traffic Control Project Progress Report", May 1966

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ECL 69C

Computerized Traffic Control (C)

City of San Jose - IBM Corporation

Operating Criteria

Jim Boring and Eugene Mahony outlined in detail to Paul Haddon of IBM Corporation the variables of traffic operation they considered of greatest importance.

1. Number of Stops
2. Delay
3. Trip Time
4. Throughput[1]
5. Queues
6. Density
7. *Speed Variation*
8. Traffic Service Index - a combination of 1,2,3, and a measure of driver satisfaction

Because of the nature of traffic and of these variables, it is usually impossible to optimize on all these variables simultaneously. Number of stops might be reduced simply by reducing the speed, however, trip time would be increased. Trip time could be reduced by restricting traffic into the control area. This procedure would reduce throughput. Throughput can

[1] Throughput. A parameter which is a measure of the number of vehicles passing through the signal system in a given period of time.

Prepared at Stanford University during the 1966 National Science Foundation Summer Institute conducted by the Design Division, Mechanical Engineering Department. This case was prepared by Donald O. Covault, Georgia Institute of Technology, Gerald A. Fleischer, University of Southern California, and Paul F. Williams, San Jose State College, participants in the Institute. The assistance of Mr. Paul Haddon and Dr. Albert Chang of the IBM Corporation, and Mr. James Boring, Traffic Engineer of San Jose and Mr. Karl H. Vesper of Stanford University was indispensable. The permission of the IBM Corporation and the city of San Jose to use this case for educational purposes is greatly appreciated.

be increased (assuming a saturated condition) by increasing the cycle length. Such an increase would be accomplished, however, by an increase in delay.

In the San Jose System, measure of items 1,2, and 3 (above) were obtained from the floating car. These results, however, reflect the performance of an individual car at isolated points in the system -- not the performance of all cars at the same time.

A scheme for measuring stops and delay with a digital computer was developed. Trip time is not feasible with a computer in a normal traffic environment, which allows turns on and off the main artery. Throughput, as a criterion, is not meaningful except in a saturated condition. Otherwise, it is simply equal to the demand. Queues at a given time are reflected in the number of stops.[2] Finally, the use of the Traffic Service Index is still experimental and requires the use of a floating car.

For these reasons, it was decided, at San Jose, that the computer measure stops and delay for evaluation purposes, these measurements to be supplemented by the floating-car measurements of trip-time, stops, and delay.

Floating Car Evaluation

During the two weeks that each control technique was in operation, City personnel drove throughout the system collecting data on trip time, number of stops, and delay. The routes chosen were the three East-West arteries for the first phase of the San Jose study and as many of the North-

[2] Using density and speed variation as criterion measures is quite difficult. One problem is that the measurements necessarily reflect the conditions at a point, or at points, whereas evaluation should be system-wide. In addition, certain densities are good under some conditions, bad under others. A speed variation of zero might mean that cars are moving uniformly in platoons, or that the street is completely congested.

South streets as possible. Some of the North-South streets contained only two intersections in the control area, so that results for them are not very meaningful. However, it was felt that some measurements were necessary because some control techniques might achieve improvement in East-West flow at the expense of the North-South streets. Therefore, average delay and probability of stopping are analyzed for these streets.

An attempt was made to follow a schedule so that trips made for one technique were made at approximately the same time of day as for another technique.

Because of the amount of time involved (about six hours a day), it was necessary to use two drivers in the study. They attempted to drive as the "average" car, which is an essential part of floating car measurement.

For a particular trip, the data recorded are trip time, number of stops, and delay per stop. Trip time is the elapsed time of the trip. A stop is counted if it is due to a traffic light in the control area. Delay is an estimate of the number of seconds lost due to the stop. A stop due to extraneous causes, such as an accident, illegally parked or turning vehicle, a stalled car, etc., was recorded but eliminated from trip time and delay. If these delays were excessive, the trip was discontinued and not used for analysis. Another cause for throwing out data was inclement weather. If the driver felt that poor visibility or wet pavement slowed him down, the data was not used.

For analysis, a trip on a particular street was classified as to direction and time of day. Over the two-week control period for each technique, the mean trip time, mean stops, and mean delay were computed. These means were for a particular street, direction and time, so that for one street

there were five means -- two for direction, three for time -- for each variable, or 15 total.

After data for two techniques were gathered, the performance of the techniques was evaluated by performing a t-test[3] on each pair of means. For one street, 15 t-tests were required.

When all comparisons were complete, the data were summarized by emphasizing significant differences. This type of summary is necessary since the results of several t-tests cannot be combined into a single overall statement. Where trade-off between control technique exists, interpretation becomes difficult. However, where one technique is clearly superior to another, this fact is usually evident from a consistent superiority.

The floating car results are discussed in the Results section of this report, and enumerated in the Appendix.

Computer Generated Evaluation Information

How Stops and Delay are Measured

A measure of system stops and delay can be obtained from the digital computer. These measurements were made at 163 detectors in the first phase of the San Jose study. The method of measurement was as follows:

1. Number of stops (refer to Exhibit C-1)

   In each approach lane to an intersection we obtained from the detector in this lane the number of actuations between end of green phase less vehicle clearance time and end of red phase less vehicle clearance time. This formulation assumes that the detector is at a sufficient distance from the intersection that no cars will be queued

---

[3] A statistical technique for determining if differences between means can be reasonably attributed to non-chance factors, such as real differences between control techniques.

behind the detector. If this is not true, all stops will not be counted.

2. Delay

Delay was defined as time lost at the intersection by those vehicles which are stopped.

The following symbols are used:

t_G - time at which green phase ends

t_R - time at which red phase ends

D - distance of detector from intersections

V - speed of traffic in free flow

tj - time during the interval $t_G - \frac{D}{V}$ and $t_R - \frac{D}{V}$ at which the jth actuation occurs.

dj - delay experienced by the jth vehicle.

All vehicles crossing the detector between times $t_G - \frac{D}{V}$ and $t_R - \frac{D}{V}$ are assumed to be stopped by the red light.

The formula for delay to the first stopped vehicle is:

$$d_1 + R - t_1 - \frac{D}{V} + H_1$$

where R is the length of the red phase, t_1 is the elapsed time in seconds after $t_G - \frac{D}{V}$ that this vehicle crossed the detector, $\frac{D}{V}$ is travel time from the detector to the intersection, and H_1 is the time lost in accelerating by this vehicle.

For n stopped vehicles the total delay for the n vehicles is:

$$D_n = nR - \sum_{j=1}^{n} t_m - n\frac{D}{V} + \sum_{j=1}^{n} H_j \quad .$$

The computer has a running record of the second term on the right of this equation, and can easily compute the first and third terms. The final term can be determined either from a mathematical model or empirically.

Empirical values of $\sum_{j=1}^{n} H_j$ will vary due to composition of traffic, turning novements, presence of pedestrians, etc. It will also likely vary from one intersection to another. Obtaining measurements on through lanes might overcome some of these difficulties. As in determining number of stops, this technique applies only when no cars queue behind the detector.

Other Factors

In addition to the previously described measurements, the following were measured, but not used for any overall, conclusive evaluation:

Volume -- On all detectors, for each approach, by time of day, for each 5 minutes

Speed -- Five minute averages for each of 30 detectors, assuming a vehicle length of 17.1 feet

Lane Occupancy -- Five minute average on each of 30 detectors.

Delay was chosen as an overall measure of effectiveness for the operation of the signal system even though this measurement was subject to some inconsistencies because of variable demand and frequency at each intersection. Delay was evaluated in two ways:

(a) Average overall delay for all vehicles in the system

(b) An evaluation of delay versus demand using regression techniques.

In addition to delay the results of the floating car method were to be used to measure the effectiveness of the signal system.

Systems Tested

Haddon, Mahoney and Boring decided to test several operating systems as described below. The computer was made to behave like other dial systems which normally change cycle length and other parameters based upon control by

a master clock. The differences was that instead of a master clock, the computer and its clock controlled the output to initiate these changes. Also, there was now a means of evaluating systems by analyzing the detector results.

Generally speaking, the computer acted like the standard systems being tested, but provided the extra monitoring and measuring capability that is a unique feature of computer systems. The following traffic control schemes were evaluated:

1. "Original" System

   This was a combination of vehicle-actuated controllers and a non-interconnected single dial system on the arteries under initial control. For the downtown section, an interconnected three-dial system was considered the "original" system, or reference point. It is important to note that both of these base line references were installed using computer generated input data to establish the timing. Therefore, the base line is actually an improvement of what was being used before the project began.

2. Single Dial

3. Three Dial

4. Three Dial Volume Actuated

   For the above three systems, the computer used tables that were set up by the City of San Jose traffic engineers according to generally accepted traffic engineering methods. The three dial volume-actuated system is the same as the three dial system, except that it changes "dials" based upon measured traffic volumes rather than by a time-of-day clock.

5. Research Program I

This technique was based upon tables that were generated by IBM Research Engineers at San Jose. It utilizes a "policy improvement" method which yields, by iteration, better and better synchronizing schemes, starting with some arbitrary first approximation. The figure of merit of this method is that the total delay to the users of the system is minimized. This delay is computed by simulating the motion of cars through a system and taking into account the size of queues stopped at the beginning of the green phase. The technique was used for either arterial or network configurations. (See operating strategies for Research I for additional information.)

6. On-Line Progression

The on-line progression program was a technique developed by D.W. Brooks of IBM. It utilizes a program that gives a maximum bandwidth for progressive arterial flow. The way it is used in real time was to recalculate the results and install a new progression every 15 minutes. This program also was "tuned" at the central location by observing the number of cars stopping at key intersections, and manually inserting parameter changes to minimize this number. This program was only used for a short period of time as a real time program because it always operated the signal system in the same manner over a short period of time. As a result, little data was obtained for this type of operation because it was discontinued after being used for three days.

7. Micro Loop Techniques

These techniques are used to control timings at any critical

intersection. There are several versions:

Micro Loop Version IA

This version holds the offset on the major street and adjusts the split only. It maintains the minimum "Walk" and "Don't Walk" timings.

Calling a certain level of demand on the 'A'phase "X", and a level of delay on the cross street "Y", this algorithm works as follows:

> If the demand on 'A; phase is more than 'X' and the delay on the cross street is less than 'Y', 'A' phase is expanded to the maximum.
>
> If the demand on 'A' phase is less than 'X' and the delay on cross street is more than 'Y', than 'A' phase is cut down proportionally to serve the cross street sooner.
>
> If there is no cross street requirement or if the demand on 'A' exceeds another fixed value, then the cross street phase will be cut sooner; to get to 'A' phase before its normal offset.
>
> If both 'X' and 'Y' are exceeded, the background cycle timing will stay in effect.
>
> If both 'X' and 'Y' are below set values, the background cycle timings stay in effect.

Micro Loop Version IB

This technique is similar to IA, but does not try to hold the offset. It expands the existing phase as it is needed, and cuts the existing phase if the opposite demand exceeds a set level. If there is no opposing demand, the existing phase is expanded to a maximum of two cycle lengths.

Micro Loop Version IIA

This is a micro-loop that works with intersections that do not have split timing on the left turn (3rd phase). It allows for a

minimum of 6 seconds for the left turn lane, and extends 3 seconds per car up to a maximum for the left turn phase.

Micro Loop Version IIB

This works the same as IIA, except that it is used with split-timings on left turns. It will end the first ('C_1') phase as described above, and then operate on the split ('C_2') phase in the same manner, thus possibly adding the excess time from C_1 to C_2.

Micro Loop Version IIC

This version operates on all three phases.

Five seconds before the scheduled end of the 'A' phase, the number of cars requiring service in all four directions for the next 10 seconds is measured. Stopped cars and moving cars are considered, and factors can be applied to weight the directions differently if there is a need because of peculiar local conditions.

The computer then compares the number of cars in both directions to determine if the current phase should be extended. As an example, if in 'A' phase the equation could be

Z = 2 (east-west cars) - 1.5 (north-south cars)

If Z is greater than set limits, 'A' phase is extended 5 or 10 seconds.

If Z is less than a set limit, it cuts of 'A; 5 seconds early.

If Z is between certain values it stays with the background timings.

This version also can set limits to stay within (5 seconds) a certain value of the normal offset. If there is no extension the program will correct toward the exact value of the offset at a predetermined rate.

Operating Strategies for Systems

Strategies for the operation of the "Original", "Single Dial", "Three Dial", and "Three Dial Volume Actuated" were specified by Jim Boring and Eugene Mahoney. These strategies were developed based on experience and standard traffic engineering techniques such as the use of time-space diagrams to determine signal offsets and phase times for arterial street flow.

The strategies for "Research I System" was developed by Dr. Albert Chang of the IBM Corporation. Dr. Chang, a young electrical engineering graduate from the University of California, was employed by IBM in the Fall of 1964 immediately after completing his Ph. D. program. Dr. Chang was assigned the task of developing an operating strategy for the signal system. By the time Dr. Chang had started to work on this problem, the basic signal system and detector locations had been chosen.

Chang discovered that several previous persons had treated traffic flow as a discrete process, i.e., individual cars in a traffic system were treated as part of the mathematical model development. Chang decided that this approach not only required very complex mathematics for model development, but it also required a very large computer facility to process rather trivial problems. Consequently, Chang treated the flow of traffic as a continuous process and therefore could consider the flow of vehicles as a mass process instead of a process whose characteristics were formulated in terms of individual vehicles. This approach permitted computer evaluation of the flow process and the use of less complicated models than would be required if traffic were considered as a discrete process.

Using this concept Chang developed the following model.[4] The sketch shown in Exhibit C-2 indicates a queue of vehicles which are waiting at an intersection during the red phase of a signal cycle. The number of vehicles flowing from intersection i to intersection j is $f_i(t)$ and the flow of traffic from intersection j is $f_j(t)$. The number of vehicles in the queue at intersection j is $j_j(t)$. Assuming instantaneous acceleration of cars waiting at j and that all cars travel at constant speed v_{ij} when the light turns green, the following equations were developed.

$$(1.) \qquad f_x(t) = f_i\left(t - \frac{d_{ij} - x}{v_{ij}}\right)$$

Where $f_x(t)$ is the flow at a point a distance x from j extending as far back as s, d_{ij} is the distance from i to j, and t is the time the cars leave the intersection.

Using equation (1), the queue at j at time t is given by the following equation:

$$(2.) \qquad q_j(t) = q_j(0) + \int_0^t \left\{f_i\left(\tau - \frac{d_{ij} - \rho_j q_j(\tau)}{v_{ij}}\right) - f_j(\tau)\right\} d\tau.$$

Where j depends upon the number of lanes between i and j denotes the length per queued car at j, is the time which can vary between the limits o,t. In deriving (2), the length of the queue, $\rho_j q_j(\tau)$, has been assumed to be less than d_{ij} in the interval (0,t).

To develop a model for the flow variables it is convenient to think of flow as arising from two components. First, if the signal at j is green

---

[4]For more complete information, see "Synchronization of Traffic Signals in Grid Networks" by Albert Chang. Paper is to be published in the <u>IBM Journal of Research and Development</u>, January, 1967.

in the direction of (k,j,) and there is no queue at j, then the flow leaving j is the flow at i delayed by the travel time $\frac{d_{ij}}{v_{ij}}$. If a queue should form at j, it will give rise to a component of f_j once the signal has turned green.

Assuming that cars leave queues at a constant rate and accelerate to their desired velocity in a negligible amount of time, the second component of flow is equal to a constant, v_j, whenever $q_j 70$ and the signal j is green. Note that the two components of flow are mutually exclusive because a queue interrupts the free flow of vehicles from the previous intersection.

Let $I_{q_j}(t)$, the indicator function of q_j, be defined as

$$I_{q_j}(t) = \begin{cases} 0 \text{ if } q_j(t) = 0 \\ 1 \text{ if } q_j(t) \quad 0 \end{cases}$$

Then, combining the two components, the flow leaving j at time t is given by

$$f_j(t) = \begin{cases} 0 \quad \text{if signal is red} \\ r_j I_{q_j}(t) + \left(1 - I_{q_j}(t)\right) \; f_i \left(t - \frac{d_{ij}}{v_{ij}}\right), \text{ otherwise.} \end{cases} \qquad (3)$$

In (3), the amber phase is ignored; it may be considered as part of either the red or green phase.

Equations (2) and (3) were derived for intersections j in the "interior" of the network. For an intersection on the boundary, the flow from i in (2) and (3) is replaced by a source: $f_i(t)$ is set equal to some prescribed function. In principle, the source waveforms should be chosen to match as closely as possible the flows observed empirically. However, except for the average number of cars which the source should supply per cycle, the exact shape of the waveform to use is generally difficult to determine. To solve this difficulty, the following simplifying assumption was made. Cars arrive

at the system boundary intersections in platoons and within each platoon the cars arrive separated by the same time interval. Furthermore, the temporal arrival pattern repeats itself from cycle to cycle. Therefore, the source waveforms are periodic piecewise constant functions.

Assuming that there are no turns, the model is complete.[5] A second important consequence of the previous assumptions in the development of the models is that the solution of equations (2) and (3) is periodic for sufficiently large t. Furthermore, the periodic solution is independent of the initial conditions of the network.

The synchronization problem for the signal system is considered next in the development of the operating strategy. One signal in the network may be chosen as a reference and the phasing of any other signal is determined by specifying the interval between the "main street green" at the two intersections. This interval, called the offset, may range from zero up to the period (cycle length) of the signals. The other signal parameter, called the split, is the duration of main street green. Its value is restricted by such factors as pedestrian crossing times. The synchronization problem is to specify the offset and split of each signal, within their permissable range, to accomplish some objective.

The criterion which was used to judge the performance of a set of signal parameters is the total steady state delay in the network which we define as

$$D = \sum_j \int_0^T q_j(t)dt. \tag{4}$$

In (4), T is the period of the signals, and the $q_j(t)$ are the steady state solutions of (2) and (3) for some fixed set of sources. The sum is taken over

[5] Turns can be modelled by introducing sources and sinks within the networks without substantially changing the theory.

all intersections and directions in the network. D is a function of the signal parameters alone, and the objective is to find a set of these variables which minimizes D.

Because of the structure of D, there is probably no fool-proof algorithm for minimizing D short of evaluating all possible signal settings.[6] As the latter is not computationally feasible even for moderate size networks, it is necessary to resort to heuristic search procedures. The procedure, which has been used with some success, normally consists of two stages. Usually a course search which may involve dividing the given network into subsystems is carried out first. The result obtained is then used as a starting point in a finer search for a local minimum of the function.

A series of look-up tables were developed using these models which would specify signal setting for various source conditions. The tables were developed using the IBM 7094 computer because a large sized computer was required to solve the delay algorithm. These tables were then placed in the memory of the 1710 computer system and called out when specific "source values" were measured by the detectors.

Chang admitted that his models are far from being perfected, but he believes that the procedure is promising and that the results obtained so far are encouraging.

The models for inclusion of the micro-loops into the system were not developed at the time of the writing of this case because of the difficulties in treating the arrival of vehicles at intersections as a random process.

[6]For a given cycle length for an entire system, the signal settings are the offset and split timings.

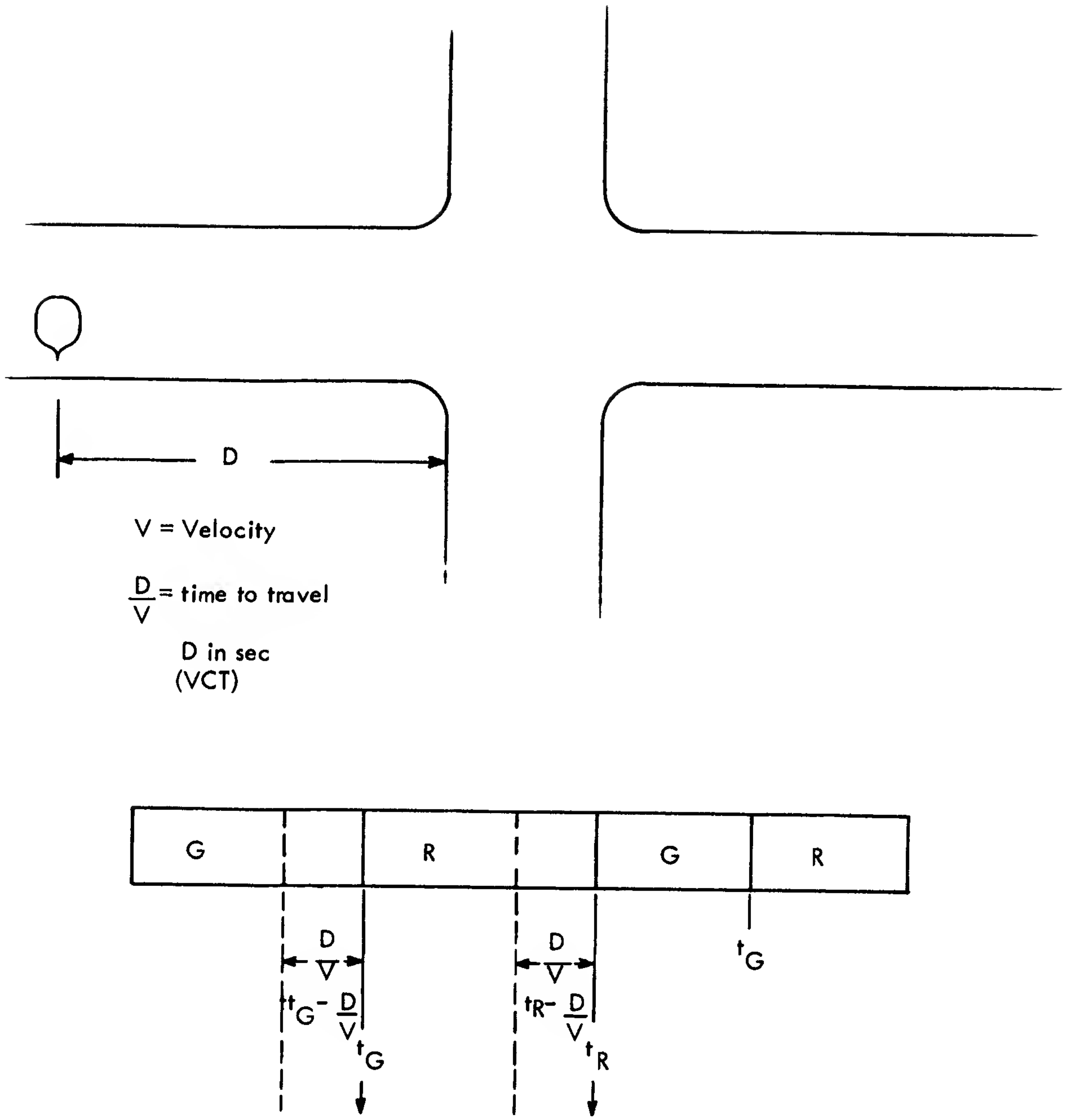


EXHIBIT C-1 MEASURING STOPS AND DELAYS AT AN INTERSECTION

Source: IBM Corporation, "San Jose Traffic Control Project Progress Report", May 1966

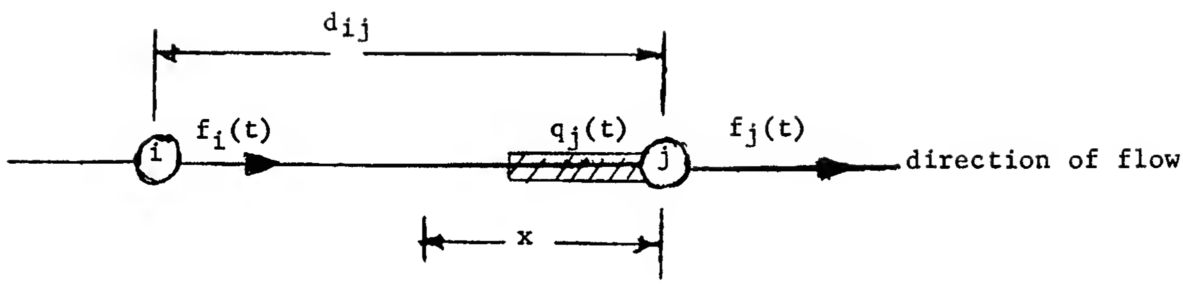


EXHIBIT C-2 Schematic Representation of One Direction of Traffic at a Pair of Intersections

Computerized Traffic Control (D)

City of San Jose—IBM Corporation

Summary of Results of Feasibility Study

In April 1966, the IBM members of the Traffic Control Project prepared a progress report. Paul Haddon, State and Local Government representative of the Data Processing Division, headed up the team. Their conclusions concerning the benefits of computerized control of traffic were as follows:

Since June of 1965, the project has been one of continuously measuring and testing both old methods and new ideas, to improve the system from a traffic and an operational viewpoint. This work is still continuing, and there are several new techniques that remain to be tried and improved upon.

 Prepared at Stanford University during the 1966 National Science Foundation Summer Institute conducted by the Design Division, Mechanical Engineering Dept. This case was prepared by Donald O. Covault, Georgia Institute of Technology, Gerald A. Fleischer, University of Southern California, and Paul F. Williams, San Jose State College, participants in the Institute. The assistance of Mr. Paul Haddon and Dr. Albert Chang of the IBM Corporation, and Mr. James Boring, Traffic Engineer of San Jose and Mr. Karl H. Vesper of Stanford University was indispensable. The permission of IBM and San Jose to use this case for educational purposes is greatly appreciated.

Some of the more important results and conclusions are summarized below:

By both computer measures and through the use of timed vehicle operations, techniques were used that significantly improved traffic flow. This improvement was evidenced by reductions in delay and stops in traveling through the system, and also in reduced trip time.

The average delay per vehicle was reduced by as much as 14% when viewing the initial phase, and by larger amounts on sub-sections of the system. The probability of a stop was reduced by 17.8%.

These reductions (for the initial phase of the project alone) result in an annual savings of more than a quarter million dollars to the motoring public.

These improvements were extended significantly through the use of Micro-Loop techniques, (which concentrated on critical intersections) and through on-line progression changing.

The feasibility of the use of a digital computer was proven for the traffic control application. In particular, the evaluation capability, the flexibility of control and the reliability of operation were of notable value.

The computer proved to be a vanguard for maintenance, by indicating the approaching failures of equipment on the street before they became catastrophic.

Finally, the system showed that continual improvement can be effected by a steady program of analysis and a study by traffic engineers. It gave traffic engineers the ability to attack problems on an overall systems basis, as well as at an individual intersection. It demonstrated that while much has been done, much more remains to be done; and that the digital computer can serve as an effective tool along the way.

Average Delay

The results of the five systems evaluated are tabulated below.

	Avg. 12 Hr. Demand in 100,000Veh.	Avg. 12 Hr. Delay In 1,000,000 Veh. Sec.	Avg. Delay Per Veh. In Sec.	Percent Improvement Over Original
Original	5.53	6.97	12.6	---
Single Dial	5.62	6.46	11.5	8.7
3-Dial (Time Act.)	5.49	6.20	11.3	10.3
3-Dial (Vol. Act.)	5.93	6.64	11.2	11.1
Research 1	5.97	6.45	10.8	14.3

These results were corroborated by regression analysis as shown in Exhibit D-1. A detailed explanation of this use of regression analysis is in the Appendix. Even though there was some question about using delay per vehicle as the only criterion, Haddon felt that it gave a good representation of the system performance.

Even though the floating car was used to collect a large amount of data and this data was subsequently analyzed for statistical significance, Haddon felt that the use of the floating car was somewhat inferior to the other means of evaluation. He gave several reasons:

a) It did not provide continuous, twelve-hour data;

b) At any given time it gave a picture of what is happening to one car at an isolated point, not a snapshot of the complete system;

c) The performance of the floating car was necessarily a function of the driver which in no way reflects the performance of all kinds of drivers.

The floating car evaluation showed that the Three Dial Techniques were slightly superior to Single Dial and that Research Technique I was significantly superior to either Single or Three Dial Techniques.

Two other methods of comparing systems were utilized. Exhibit D-2 shows the percent improvement over the original system by each of the alternates for each intersection in Phase I. The average delay at each intersection for the original system and the Research System is shown in Exhibit D-3.

<u>Probability of a Stop</u>

The probability of a stop was calculated by dividing the average number of stops by the average demand. The computer results for the original system and the Research Technique were as follows:

	Original	Research
Average Number of Stops	2.33	2.23
Average Demand	4.40	5.12

Economic Evaluation of Stops and Delays

One of the elements included in the IBM Progress Report was an analysis of the costs of Stops and Delays to the motoring public. They used the following figures from the American Association of State Highway Officials (AASHO) report entitled, "Road User Benefit Analysis for Highway Improvements": The (AASHO) figures are based on 1959 cost data and nation-wide averages.

Gasoline	$ .32 per gallon
Oil	.45 per quart
Tires	100.00 per set initial cost
Time	1.55 per hour

Car repairs and car depreciation are included.

The AASHO cost figures for a 30 m.p.h. approach speed are:

$.74 = Cost of a vehicle stop
.008 = Cost after second, idling
.043 = Cost after second, waiting

The cost of stopped delay for the original system was calculated from computer data as follows:

Average delay per stop	=	23.75 seconds
Average 12 hour demand	=	553,000 vehicles
Cost per stop	=	.74 + 23.75 (.008 + .043) = 1.9512 cents per stop
Cost per day	=	number of stops x cost per stop (Number stops = probability of a stop x 12 hour demand; probability of a stop = $\frac{\text{mean stops}}{\text{mean demand}}$)
Cost of stopped delay Per day for original system	=	$\frac{2.33}{4.40} \times 553{,}000 \times \frac{1.9512}{100} = \$5713$

The cost of stopped delay for the Research Technique, using a similar calculation, is given below. For purposes of comparison, the same 12 hour demand figure was used, even though Research actually encountered a greater demand. The average delay per stop = 24.82 seconds.

Cost per stop = .74 + 24.82 (.008 + .043) = 2.0058 cents

$$\text{Cost per day} = \frac{2.23}{5.12} \times 553{,}000 \times \frac{2.0058}{100} = \$4831$$

Savings per day = $882
Savings for one year (300 days) = $264,600

In summarizing the Economic Analysis, the IBM team made the following statement:

> It can be seen that reduction in the probability of a stop (17.8%) and the reduction in total delay resulted in extremely significant reductions in cost to the motoring public. It should be emphasized that this savings of $264,600 is only for the first 32 intersections, and represents conservative figures for delay and stops, in that not 100% of those stopped are detected. Expanding the control to Phase II, and then over large areas which the same computer could control will result in even larger possibilities of saving. It shows conclusively that even a little attention to seemingly small improvements, in the future, can result in very large cost reductions.

Proposed Operational System

In May 1966, Jim Boring prepared a memo for the Director of Public Works to send to the City Manager. It recommended, on the basis of the results of the feasibility study, that the city adopt an operational computerized traffic-signal control system. Refer to Exhibit D-4. The Traffic Control Project Report prepared by the IBM team was attached to the memo.

A. P. Hamann, City Manager, scheduled the proposal for the next meeting of the City Council. In anticipation, Boring prepared additional support for his recommendation. Financing the proposal and indirect benefits were the two areas on which he focused. The indirect benefits, according to Boring, would be as follows:

> To Budget Officials
>
> 1. Traffic signal elements and components are becoming more sensitive, intricate and expensive to purchase, install and maintain. In this view, the computer method would:
>
> a. House and protect centrally the expensive portion of the equipment; expose the less costly elements to weather and road damage or destruction by vehicle collision.

b. Reduce the man-hours required by people for field measurements, and field to office travel time.

c. Increase efficiency of analytical personnel in that data collection and array presentations are prepared rapidly and automatically.

d. Assist in reliability evaluation of field components, such as controllers and detectors.

e. Tend to reduce the complexity and expense of additional equipment for modification of existing or new installations. Upgrade system by installation of less expensive field components.

<u>To City-County-State Transportation Officials</u>

a. The system is installed and operating.

b. It is easily expansible.

c. It crosses a State freeway (17 at West San Carlos).

d. It could assist by providing traffic data for area network studies such as assignment studies involving integration of the major city streets-county expressway-state freeway complexes.

e. It provides continuous data collection and means of measuring and comparing imposed network strategies.

f. 1. Data collection characteristics are flexible:
   ...as to ease of location or relocation of individual field sampling points
   ...as to type of field sampling detection equipment
   ...as to concurrent or alternating traffic measurements required.
   2. Imposed control strategies including traffic parameters may be changed wholly or in part at a central site.
   3. Surveillance of controller and detector gear with visible and audible alarming is possible.
   4. Analysis and evaluation of strategy performance from stored data measurement and calculation arrays may be made, from curve or listing output.
   5. Simulation techniques are possible
   ...Traffic control for construction parallel to State Freeway

The major element in the proposed system, from a financial standpoint, was the IBM 1800 computer system. IBM suggested three ways for the city to acquire this equipment—rent, rent with purchase accruals, and the state and local government purchase plan. One of the factors that Jim considered in

evaluating these plans was the constraints placed upon different sources of funds by Municipal laws. Capital bonds could be used for the purchase but not the rental of equipment. Funds for the rental of equipment would have to come from general tax revenues which were limited.

The straight rental plan was fairly simple. For a fee of $4700 per month the city would have possession of the equipment. Maintenance services would be included at this price.

The rental with purchase accrual plan had a provision that a portion of each month's rent would apply towards purchase. The monthly charge for this plan would have been $4825 for the first 75 months and $2181 for the 76th month. At the end of this period, the system would become the property of the city. Maintenance would be provided by IBM during the rental period.

The state and local government purchase plan was characterized by the fact that the city would own the equipment immediately, but pay for it over 60 months. The city's payment schedule would be as follows:

Lump Sum Initial Payment			$29,193.00
Monthly Payments,		first 6 months	3,783.52
"	"	next 12 months	3,604.61
"	"	" "	3,488.23
"	"	" "	3,371.85
"	"	" "	3,255.46
"	"	last 6 months	1,238.17

These figures include a $224.25 charge for minimum monthly maintenance. The list price of the 1880 system is $194,620.

The 1800 system superceded the 1620 in the IBM product line. It was less expensive than the former system and had greater capacity—up to 400 intersections. IBM will install an 1800 system, their first sale of this equipment for traffic control, in Wichita Falls, Texas, in late 1966.

In July 1966, the City Council voted to establish an operational computerized traffic signal control system as recommended by Jim Boring. The only discussion of the proposal concerned the site of the proposed facility.

The regression lines for each technique show improvement at each stage of the experiment. Three-dial, time actuated, improved over single dial; three-dial, volume actuated, improved over three-dial, time actuated; Research Technique I improved over three-dial, volume actuated. The chart shows that the nature of the improvement is highly desirable, in that the greater savings in delay are realized at the high volumes.

The number of points for each regression line is determined by the number of cycles for all days that the technique was tested. The smallest number for any technique is 145,000, so the statistical significance of the results cannot be questioned.

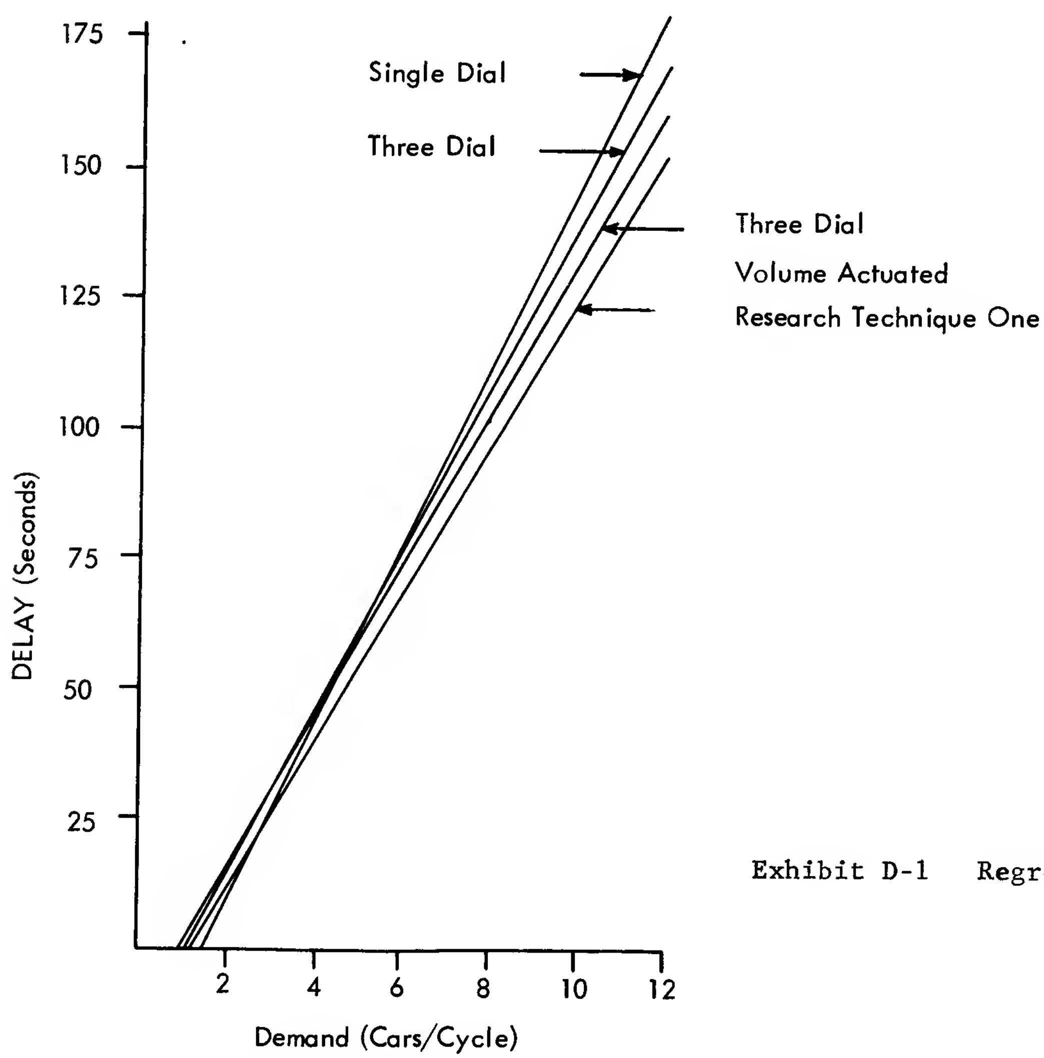
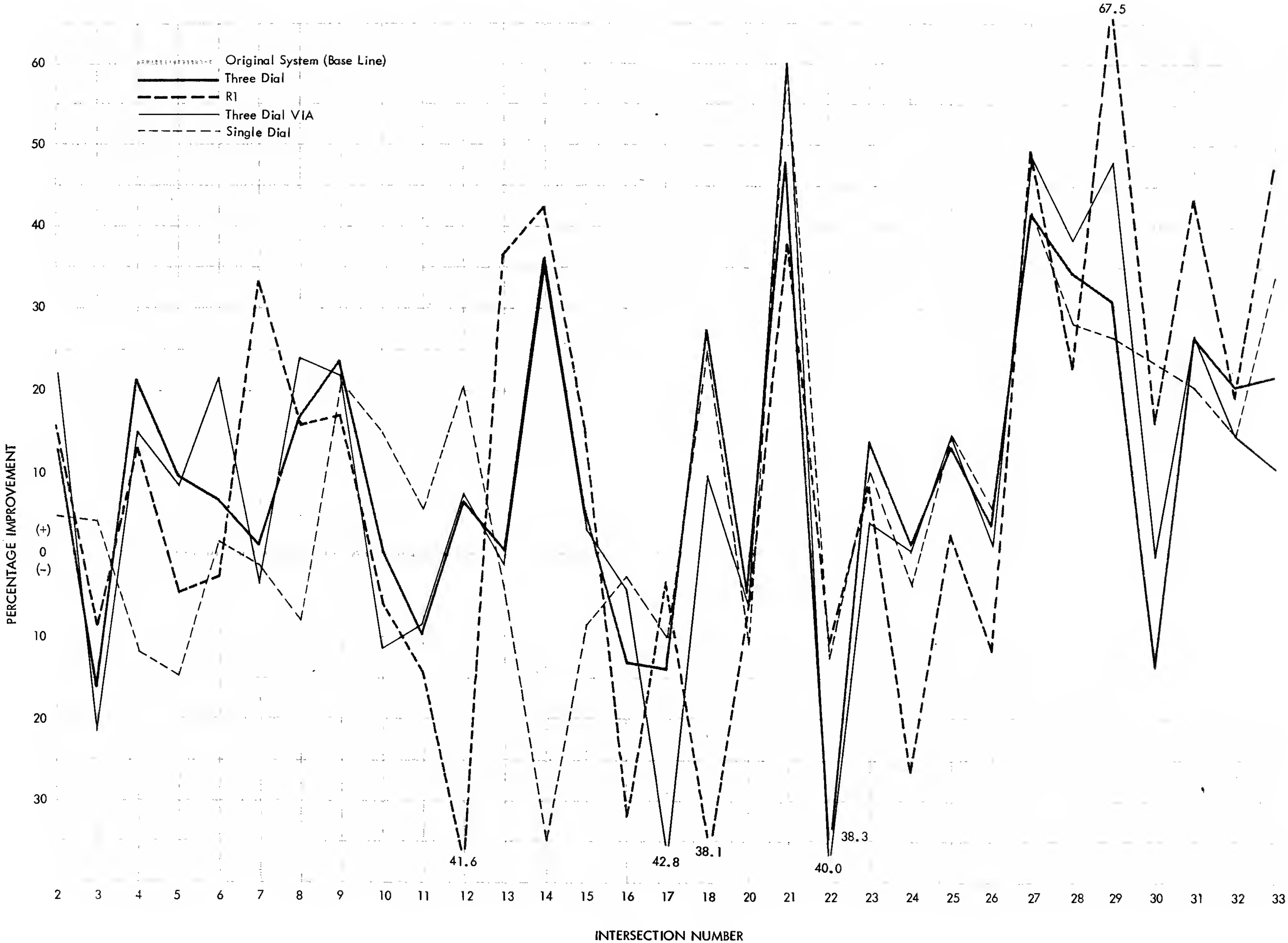


Exhibit D-1 Regression Analysis



Original System (Base Line)
Three Dial
R1
Three Dial VIA
Single Dial
PERCENTAGE IMPROVEMENT
60
50
40
30
20
10
(+)
0
(-)
10
20
30
67.5
41.6
42.8
38.1
40.0
38.3
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 20 21 22 23 24 25 26 27 28 29 30 31 32 33
INTERSECTION NUMBER

Exhibit D-2

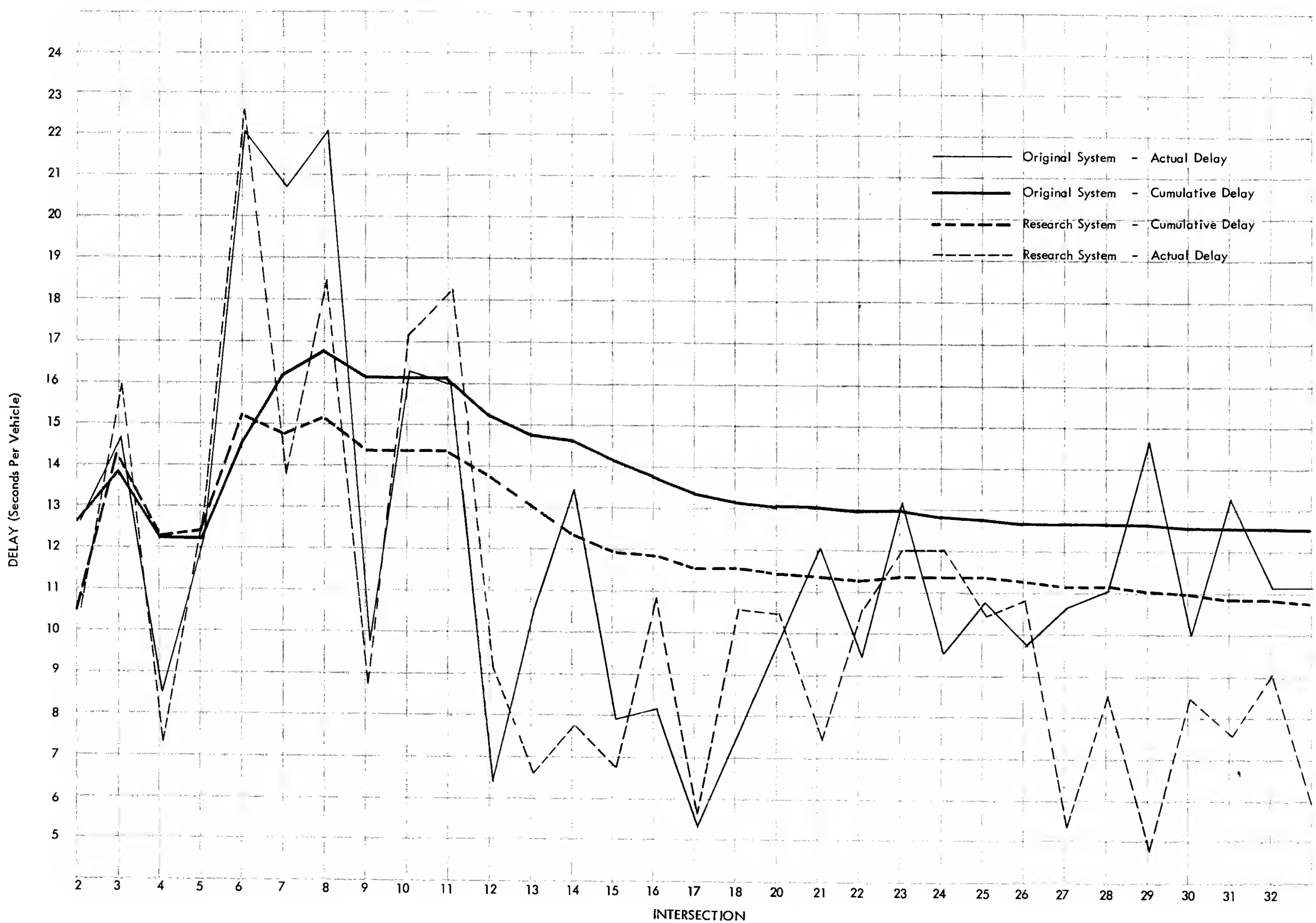

Original System - Actual Delay
Original System - Cumulative Delay
Research System - Cumulative Delay
Research System - Actual Delay
DELAY (Seconds Per Vehicle)
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 20 21 22 23 24 25 26 27 28 29 30 31 32
INTERSECTION

Exhibit D-3

CITY OF SAN JOSE -- MEMORANDUM

TO A. P. Hamann, City Manager

FROM A. R. Turturici
Director Public Works

SUBJECT Computer Traffic Control

DATE May 26, 1966

Wilbur Smith and Associates, upon completion of an intensive traffic and parking study, submitted to the City a report entitled "San Jose Central Business District Traffic Study." One of the recommendations in this report was that the signal system in the Central Business District be modernized by interconnecting the signals and installing three dial, fixed time controllers.

A fixed time system has several drawbacks in traffic control. It is not responsive to changes in traffic flow. It cannot adjust itself to handle variable peak loads due to special events such as special sales, parades and Civic auditorium attractions. On the other hand, the existing traffic responsive systems were very expensive, requiring a complete change of all local controllers to make it operable.

Considering these items, a joint traffic control project in cooperation with I.B.M. was undertaken. The primary purpose of the project, as stated in the agreement with I.B.M., was to determine if it would be functionally and economically feasible to use a digital computer for traffic control.

The signals in the Central Business District have been frequently under computer control during the past year demonstrating that it is feasible to operate the signal system with the computer. With the new line of computers, the Model #1800 in particular, the capitol outlay required to install a traffic responsive system controlled by the computer is less than previously used systems. It has been demonstrated that under computer control there is less vehicle delay in the system which in turn provides greater capacity to the street system. Thus, we have, at last, a machine which can do more efficiently that which almost all signals were installed to do; that is, aportion the intersection right-of-way in relation to the demand.

Other services that the computer system will offer that no other traffic control equipment can duplicate are:

1. Continuous surveilance of both street traffic conditions and equipment operations.

2. Provide central site for traffic monitoring and control changes which reduces the need for counting and observing personnel on the street corner.

3. Evaluate data collected to provide information on quality of traffic flow.

4. Process traffic flow data from all parts of the City which will be fed in by radio (the radio system is in operation).

It is anticipated that the computer will be required to operate signals approximately 12 hours a day. The exact time depends on special events which would require extra time. This will allow the machine to be available several hours a day to be used for other programs such as traffic assignment, accident analysis, engineering calculations, maintenance programming and many others.

It is recommended that:

1. The present computer be kept operational until the expiration of the City's agreement with I.B.M. (January 1, 1967) - $17,000.

2. A firm order be placed for a model #1800 computer to be delivered in December 1966; to be paid for on a State and local government purchase plan requiring a $30,000 down payment and approximately $3,700 a month.

3. A site to be prepared in the Civic Center area for a traffic control site as the existing location must be vacated shortly. (An existing duplex or acquire another within the area of Civic Center expansion). Existing building modified - $10,000; Purchase building and modify - $60,000.

4. An agreement be entered into with P. T. & T. to lease underground duct space to bring the interconnect to the Civic Center - $1,500 a year. Install interconnect cable to Civic Center - $80,000.

5. The classification of Computer Programmer be established and the two persons doing this job now be reclassified - no cost.

The cost to set up the traffic control site at the Civic Center is the same regardless of the type of traffic responsive control system used. The total cost of installation would be approximately $90,000 if City-owned structure is used. The cost would be increased by approximately $50,000 if additional property is acquired.

The accompanying reports are for you and the City Council and describe the project and its benefits in more detail.

Respectfully submitted,

A. R. Turturici
Director of Public Works

ART:JWB:vcj

Exhibit D-4 (continued)

Appendix

(Source: IBM Progress Report, May 1966)

The Use of Delay in Evaluating Systems—Regression Analysis

A comparison of two control techniques on stops or delay, would be meaningless without taking into account the number of cars requiring service (demand). The question arises as to how to take this variable into account. One possibility (which has been used by traffic engineers) is to divide the total number of stops by the total demand and use this figure for comparison purposes.

This figure of probability of a stop, or delay per vehicle, is not entirely satisfactory because of its dependence on fluctuations in demand. Consider the following results, for two imaginary techniques, A and B.

Technique A—Cycle Length = 60 seconds			
Demand Cars/Cycles	Frequency of Occurrence	Delay Sec/Cycle	Delay Sec/Vehicle
2	20	20	20
4	20	60	15
6	20	100	16 2/3
8	20	140	17 1/2
400 cars total demand			

Technique B—Cycle Length = 60 seconds			
Demand Cars/Cycle	Frequency of Occurrence	Delay Sec/Cycle	Delay Sec/Vehicle
2	16	20	10
4	20	60	15
6	20	100	16 2/3
8	21	140	17 1/2
400 cars total demand			

Here, we have two techniques where the only difference is that the frequency of occurrence of demands changes. The delay per cycle and delay per vehicle for each level of demand are unchanged. The important feature to note is that each technique handles the same demand in the same manner. A driver who is in a platoon of 2, 4, 6, or 8 vehicles will experience the same delay regardless of which technique in in operation. A traffic engineer forced to choose between the two techniques might just as well toss a coin. He cannot be expected to anticipate the frequency of occurrence of each level of demand, especially when random deviations can have a marked effect on the criterion he is considering.

Apparently, the imaginary techniques, A and B are performing equally. Let us examine total demand and total delay.

For Technique A total demand is: 20 (2+4+6+8) = 400 cars

Total delay is: 20 (20+60+100+140) = 6400 sec.

The delay per vehicle is then 16.0 sec.

For Technique B total demand is again 400 cars.

Total delay is 6460 sec.

Delay per vehicle is 16.15.

This difference does not appear to be great. However, considering that we are dealing with vehicles in the hundreds of thousands, it takes on more significance. Thus, we can see that a difference in average delay per vehicle can exist, which may not be meaningful in the way traffic demands are being handled.

Let us examine a somewhat more drastic result for our imaginary Technique B.

Technique B—Cycle Length = 60 seconds			
Demand Cars/Cycle	Frequency of Occurrence	Delay Sec/Cycle	Delay Sec/Vehicle
2	4	20	10
4	11	60	15
6	26	100	16 2/3
8	24	140	17 1/2

Total demand = 400 Vehicles

Total delay = 7600 sec.

Delay/Vehicle = 16.75 sec.

As compared to Technique A, B yields 4.7 per cent greater delay per vehicle with total demand, delay per cycle and delay per vehicle for each individual cycle remaining constant.

The question is not so much as to how likely demands are to fluctuate— but that with two techniques yielding results which traffic engineers consider identical a method which concludes that they are identical is preferred.

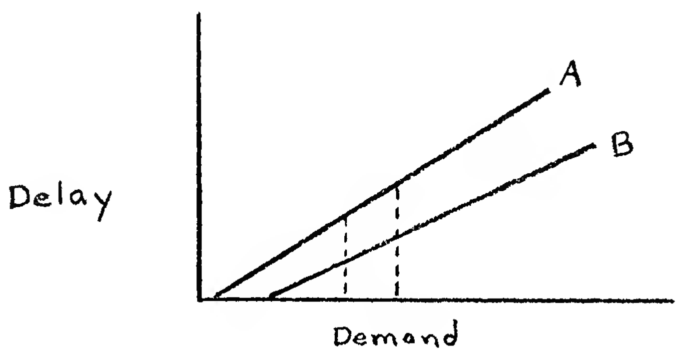
One method of analysis commonly used to accommodate fluctuations on an independent variable is regression analysis. It is the equivalent of eliminating the effect of an independent variable X on a dependent variable Y. Regression analysis, in this context is accomplished by plotting each individual demand against each individual delay. The best fit straight line which fits these points is then determined by the least squares technique, and this line represents the performance of the technique for which it was determined.

All three examples given thus far (one for Technique A, two for Technique B) would result in coincident regression lines. The average delay per vehicle would not, however, be the same. These figures are fictional, but they were chosen to show the limitation of using only average delay/vehicle.

We might consider other cases which would give identical results. The most general case would be for the line which passes through the mean delay for all levels of demand, and the variability is constant for each level of demand.

The efficacy of the linear regression line depends upon how well the line fits the data. This refers, of course, to its efficacy in representing system performance, not as compared to using delay per vehicle only. At worst, it would yield a line parallel to the X-axis, indicating that demand has no effect on delay. In this case, the delay per vehicle could still be used.

A test of goodness of fit of the linear regression line can be performed, either by analysis of variance, or by hypothesizing some form of non-linear fit, such as a parabola, exponential, etc. The analysis of variance technique merely informs you that the straight line does (or does not) fit very well. If it does not fit, you still do not know what type of curve does. To test a specific type of curve, it is necessary to determine the parameters of that curve by a technique like the least squares approach, plot the resulting curve and compare it to the line obtained by linear regression.



The total savings in delay would be for each demand level, the difference between ordinates multiplied by the frequency of occurrence of that demand.

One method of equating the two scales is to divide both demand and delay by the cycle length, and "plot" the resulting numbers. We would have a plot of demand in cars per second versus delay in seconds per second. This plot is somewhat more difficult to interpret and does not lend itself readily to a reconstruction of the total delay. However, in a truly adaptive system, where the cycle length changes frequently, such an approach may be necessary.

The advantages of using average delay per vehicle are the convenience with which it can be computed and its ease of interpretation. However, it is with regard to the latter that care must be exercised. A statement such as one technique results in ten per cent less delay than another does not give the complete picture.

Limitations of Regression Analysis

In addition to the possibility of non-linearity, other cautions should

be observed in the application of regression analysis. This results from the fact that different control algorithms may have different cycle lengths, and the comparison should not be made directly.

Consider the case where algorithm A uses a 60 second cycle while B uses a 120 second cycle, and the results over a ten-minute period are as follows:

Technique A (C = 60 sec.)		
Demand Cars/ Cycle	Frequency of Occurrence	Delay Sec/ Cycle
2	2	16
3	2	30
4	2	44
5	2	58
6	2	72

Technique B (C = 120 sec.)		
Demand Cars/ Cycle	Frequency of Occurrence	Delay Sec/ Cycle
4	1	32
6	1	60
8	1	88
10	1	116
12	1	144

Over the full time of operation (ten minutes) each technique handles 40 cars with 440 seconds delay. Technique A would handle, for two successive cycles, the same demand with the same delay that B would handle, with twice the demand with twice the delay. Apparently, the two techniques are equally effective in handling the traffic. Plotting the two regression lines would result in identical slopes, but the intercept for B would be twice that for A. Therefore, some adjustment is required.

If the intercepts for the two techniques are both zero, no adjustment is necessary. A direct comparison can be made on the slopes of the regression lines.

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INSTRUCTOR'S NOTES

to

Accompany

CITY OF SAN JOSE - IBM CORPORATION

Computerized Traffic Control

(Parts A, B, C, and D)

Introduction

It is in the nature of any case study that there are no readily defined, specific "solutions" to problems raised by circumstances of the case. (Indeed, problem definition may provide the greatest difficulty in certain instances.) These "Instructor's Notes", are intended as a set of suggested guideposts which may be used to focus upon some of the central issues which we believe to be raised here. Individual instructors will emphasize some of these issues and disregard others; and some instructors will undoubtedly focus upon entirely different problems. In any event, we hope that these brief remarks will prove helpful.

Pedagogically, this case may be used to illustrate a number of issues, among which are the following:

1. governmental decision making (capital investment, technical features)

2. evaluation of alternative strategies for traffic control

3. economic evaluation of traffic-oriented capital investment project

4. marketing an existing product for a new application

5. history of joint private industry-government research activity

6. critical discussion of validity of certain statistical techniques.

D. O. Covault

G. A. Fleischer

P. F. Williams

Palo Alto, California
September, 1966

Part A: The Decision to Enter into Joint Agreement

1. Specifically, what decisions were made by "the City" and who was responsible for these decisions?

2. Why did Blackburn suggest that IBM, rather than his office, prepare the proposal?

3. Should the City and IBM have entered into the agreement to study the feasibility of computerized traffic control? Why?

4. What were IBM's interests in the study? What had they to gain or lose?

5. What were the economic aspects of the City's involvement? Do the cost projections seem reasonable?

6. What may be said about the economy study (or lack thereof) used to support decisions?

7. Discuss the problems of risk and uncertainty associated with the decision to enter into the joint agreement.

8. What are the possible advantages and disadvantages of controlling traffic with an electronic computer?

9. Was the system selection (Exhibit A-5) envisioned in the spring of 1964 compatible with the stated objectives of the study?

10. Are frequent delays and extensions of deadlines common occurrences in development programs?

Part B: Description of Control System

1. Discuss the decision to divide the study into Phases I and II.

2. Discuss the selection of equipment, both for use in the computer control center and field installation.

3. What criteria should have been used to determine which intersections should be included in the study?

4. What criteria should have been used to select the equipment for use in the study?

5. Note the techniques used in the study to measure traffic volume and speed. What other means might be used to this end?

6. Do you think that the decision to utilize existing controllers was appropriate? Why?

Part C: Control Strategies

1. Evaluate the control strategy, "Research 1", devised by Dr. Chang.

2. Note that Dr. Chang did not join the study team until June, 1964. What would have been the effect, if any, if he had been on the project six months earlier?

3. Was Dr. Chang's use of vehicle delay as the figure of merit appropriate? Under the circumstances, would some other figure of merit have been more "suitable"? Why?

4. In addition to those systems (operating strategies) described in Part C, what others might be used?

5. Do you believe that the "floating car method" of evaluation is a suitable means of measuring the effectiveness of a given traffic control system? Suggest improvements, if possible.

6. Would you suspect that any or all of the control strategies decribed in Part C would result in a significant improvement over the "original system" ? If so, by how much?

Part D: The Decision to Adopt an Operational System

1. Make a critical evaluation of the regression analysis as discussed in the Appendix.

2. It is claimed that the Research I strategy results in a 17.8% reduction in probability of a stop over the original system. Does this claim appear to be justified?

3. Evaluate the "economy study" used to substantiate the savings of $250,000. Note that no provision has been made for traffic growth and, further, that no recovery of capital costs or annual maintenance and operating costs have been included.

4. In particular, in (3) above, note the effect of using the time value of $1.55 per hour. What is the historical basis for this value?

5. What may be said of Jim's evaluation of the alternative ownership/lease plans?

6. What justification was given for ignoring the "floating car data" ? Is this reasonable?

7. Do the results of the pilot program appear to justify the new commitment?

8. Given that the City approved the new program, what effect, if any, might this have on the future development of the City's traffic signal system?

9. Will the City be able to continue on its own without the direct assistance of IBM personnel? Why?

10. What might the City do with its unused computer time? (See Exhibit D-4)

11. At the time of preparation of this case, organizational responsibility for the computer center had not been definitely established. Should the new director report to Boring? Turturici? Someone else? Discuss the ramifications of this decision.

12. What decision rules might be used to select additional intersections for inclusion in the system?

13. What market potential would you expect for IBM in this area of computerized traffic control? Why?